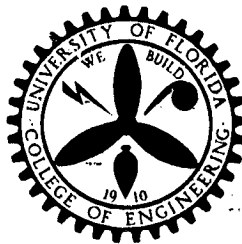


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ELECTROMAGNETIC WAVE

ENERGY CONVERSION RESEARCH

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Submitted By

University of Florida

Engineering and Industrial Experiment Station

Gainesville, Florida 32611

SIGNATURE SHEET

PRINCIPAL RESEARCHERS

Robert L. Bailey

Robert L. Bailey  
Principal Investigator  
Associate Professor  
Department of Electrical Engineering

Philip S. Callahan

Dr. Philip S. Callahan  
Entomologist  
USDA  
Insect Attractants, Behavior,  
and Basic Biology Laboratory

Markus Zahn

Dr. Markus Zahn  
Associate Professor  
Department of Electrical  
Engineering

APPROVED BY

E. R. Chenette

Dr. E. R. Chenette  
Chairman  
Department of Electrical Engineering

Derrell L. Chambers

Dr. Derrell L. Chambers  
Director  
USDA Laboratory  
Courtesy Associate Professor  
University of Florida

## ABSTRACT

This short early research effort was undertaken to strengthen the scientific base for the Electromagnetic Wave Energy Conversion (EWEC) invention (U. S. Patent No. 3,760,257). Such advanced research, it is believed, could ultimately lead to creation of a useful new family of high efficiency direct solar-electric converters. Such converters would exploit the well-known wave theory of light interacting with optically rough surfaces composed of tapered absorber elements many wavelengths long.

This initial theoretical research focussed on the EWEC absorbers, as they are an important critical element of the EWEC concept. The other critical element, the rectifier, is not dealt with in this research.

An extensive literature search revealed abundant published scientific evidence supporting the notion of electromagnetic waves interacting with rough surfaces. The relevant research literature is summarized for the first time.

The research plan was to first study known electromagnetic wave absorbing structures found in Nature for clues of how one might later design large area man-made radiant-electric converters. It lead to studying the electro-optics of insect dielectric antennae. Considerable new theoretical insights were achieved into how these antennae probably operate in the infrared 7-14 $\mu$ m range, though substantially more--theoretical and experimental--must be done for the insight to be complete.

EWEC theoretical models and relevant cases are concisely formulated and justified for metal and dielectric absorber materials. Finding the electromagnetic field solutions to these models represents a major technical problem not yet solved. Their later solution will lead to new insights into the technical requirements for both rough surface solar-thermal absorbers ("Selective Surfaces") and solar-electric converters.

A rough estimate of losses in metal, solid dielectric, and hollow dielectric waveguides indicates future radiant-electric EWEC research should aim toward dielectric materials for maximum conversion efficiency.

The research also revealed the absorber bandwidth is a theoretical limitation on radiant-electric conversion efficiency. Ideally, the absorbers' wavelength would be centered on the irradiating spectrum and have the same bandwidth as the irradiating wave.

The EWEC concept appears to have a valid scientific basis, but considerable more research is needed before it is thoroughly under-

stood, especially for the complex randomly polarized, wide-band, phase-incoherent spectrum of the sun. Specific recommended research areas are identified.

KEY WORDS: Solar, Solar-electric, Solar-thermal, Electromagnetic Waves, Electromagnetic Wave Energy Conversion, Electro-optics, Wave-Surface Interactions, Dielectric Antennae, Selective Surfaces.

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None

## Chapter 1

### INTRODUCTION

The Scope Of The Present Research Grant is limited specifically to the absorbers on a new type of direct solar converter. Before treating the details, it is important to realize this advanced energy research undertaken at the University of Florida is embedded in the larger national energy Research and Development effort, and we should have this perspective succinctly in mind at the beginning.

The National Energy Problem has been generally known for some years. The United States, and other countries, face serious energy crises as fossil fuels are being rapidly depleted.

Projections of five fold increases in total U.S. energy needs are forecast for the year 2020 [83].

The early 1970's has seen a large number of energy alternatives examined, many for the first time on a serious basis. The alternatives examined by various groups and individuals have ranged from restudying conventional energy sources and systems, e.g. coal-electric, to the advanced systems, e.g. large-scale solar-electric systems spun off from the Space Program.

Our only inexhaustible energy alternative, solar energy, is presently experiencing renewed interest and is in 1975, in toto, a rapid growth industry, particularly solar water heating and house heating. This growth industry, for all practical purposes, started with the late 1972 publication of a carefully conceived U. S. Solar Research and Develop-

ment plan [82] advanced by the NSF/NASA Solar Energy Panel. This was the first coherent solar R & D plan advanced for the nation, technical efforts prior to 1972 having largely been uncoordinated labors of love by a few solar pioneers. The report's recommendations are presently being implemented by various U. S. private enterprise, industry, government, (ERDA, NASA, et al), and university groups. In each recent year government funds allocated for solar energy related technology have grown significantly.

The Case For Terrestrial Solar-Electric Conversion was authoritatively made in the NSF/NASA Solar Energy Panel work and Report. Briefly summarized:

- Total U. S. Energy Resources Used To Produce Electric Energy in 1969 were about  $13.9 \times 10^{15}$  BTU out of a total of  $64 \times 10^{15}$  BTU. Thus to produce electric energy we used about 21.7 percent of our total energy resources. The remainder was principally used in heat related forms [83].
- The Percentage of Energy Resources Needed To Produce The Future Electric Energy required for the U. S. is expected to increase to about 55 percent by 2020 A.D. [83]
- Meeting The Numerical Increase of electric energy needed while also demanding a greater percentage of the nation's energy be in electrical form will place great stresses on:
  - Δ Our fossil fuel resources.
  - Δ The nation's utility companies -- both investor-owned and government subsidized.
  - Δ The environment.
  - Δ Our financial resources.

There is grave doubt we shall, in fact, be able to install in time the enormous electric plants required by simply extending prior technology. A faltering of the breeder reactor program, on which the government is principally depending to meet the mid 1980's increase, may be di-

sastrous to the country unless we have other bulk energy options available.

- Total Arriving Solar Energy within U. S. Continental limits in a year exceeds the present total energy required to run the country by a factor of more than 600 (a very conservative estimate). On a clear day the sun's intensity at the earth's surface on an area normal to the sun's rays is about 1 KW/M<sup>2</sup>. There is more than enough solar energy available to generate the nation's entire electric power. The problem is to find how to economically do it. The Panel's report proposed R and D needed leading to possible practical solutions to this national problem.
- Central vs On-Site solar generation of electric power was examined. R and D programs were recommended for both areas. Electric power generated by either method would relieve electric utility companies and minimize use of precious fossil fuels.
- Centralized Terrestrial Solar-Electric Generation of bulk power was shown to be attainable with a relatively modest R and D investment by the nation.
- On-Site solarly generated electric power will be possible in many U. S. areas where weather conditions are favorable. The energy converter might be solar cells, though this present-art approach requires lowering their cost several orders-of-magnitude yet before widespread use of on-site electric power generation is attained.
- No Significant Pollution by-products or environmental effluents are inherent to either central or on-site solar-electric generation -- a major advantage of solar energy utilization.
- Cost Per KWH of central solar generated electric power is presently estimated to be several times that of fossil fuel electricity. R and D is expected to decrease the cost substantially. Also present rising fossil fuel cost trends hasten the day when solar generated power can be competitive with conventional electric power.
- Known Most Promising Methods of terrestrial solar-electric conversion for generating bulk power are:

Δ Solar Thermal Methods, principally using large area thin films and "the greenhouse

effect" to achieve high temperatures required for conventional boiler-turbine-generator systems.

- A Direct Conversion Via Solar Cells exposed to the sun in large areas (kilometers square for central plants -- a few square meters for buildings).
- A Solar Tree Farms in which the sun's energy is stored as wood and later burned in a conventional electric power plant.

Many other significant facts -- too numerous to relate here -- bearing on the concepts of both central and on-site solar-electric power plants -- including the difficult problem of energy storage -- also emerged in the Solar Energy Panel work and report [82].

Direct Conversion of the sun's energy to electricity has long been recognized by many researchers as a desirable direction to proceed. A simple calculation reveals that were practical direct solar-electric converters available on a large-scale, in the U. S. alone a market potential of many billions of dollars could be opened up. The large-scale arrival of such converters would have enormously beneficial social and other impacts and permit direct utilization of our only source of energy income -- the sun.

However, virtually all who have realistically approached the problem of creating practical high efficiency direct solar-electric converters have recognized the great technical difficulty of the problem. Direct conversion of radiant energy to electricity is substantially more technically sophisticated and less understood than conversion to heat energy forms, which facts partly account for why such converters are

not yet available on a large-scale.

Direct solar electric conversion methods presently are classified as 'Advanced' in nature, as there is no present widespread implementation of such methods.

The principal present-art solar-electric converter is the silicon solar cell, largely carried to its present state of development by the U. S. Space Program. Such solar cells are now characterized by high cost and, at best, a solar-to-electric power conversion efficiency of 15 percent [39] with a theoretical maximum of about 24 percent. Solar cell conversion efficiency has remained nearly static in the 13-15 percent range since about 1962.

A Basically New Direct Approach appeared to be needed for converting radiant energy to useful electrical energy if significantly higher conversion efficiency was ever to be achieved along with the attendant beneficial social effects inherent in direct solar conversion.

Such a new concept was first advanced by Bailey in 1968 while engaged in research at Goddard Space Flight Center [4] [3]. It is called the Electromagnetic Wave Energy Converter (EWEC) and was cited specifically in the 1972 Solar Energy Panel Report as an example for which "research into new methods of solar energy conversion should be initiated"; but unfortunately this important and potentially significant research did not get started on a serious basis until the present grant.

The EWEC converter concept is briefly described in Chapter 2.

## Chapter 2

### THE EWEC CONCEPT SUMMARIZED

A Summary of the Electromagnetic Wave Energy Converter (EWEC) concept is made here because of its relative newness to researchers and others. The details are in Bailey's publications [1] [2] [3].

A Central Idea of the new EWEC concept is to attempt making use of the classical wave properties of the electromagnetic radiation impinging on the converter. The use of wave properties of electromagnetic radiation is well established in radio, radar, antenna, and allied arts, principally for transmitting and receiving signals.

The theory that visible light is a wave phenomenon is at least as old as the Dutch physicist, Huygens (1629-1695). Classical wave theory was thus well developed in optics and physics long before the more recent quantum approaches appeared. Every modern physics student knows of the dual wave-particle nature of electromagnetic radiation; nevertheless, it has been somewhat surprising -- and distressing -- to us throughout this research to find many practicing technical people having philosophical difficulty accepting the wave viewpoint, especially as one enters the infrared and visible ranges.<sup>1</sup>

Since the physics of modern silicon solar cells -- which is now a well established technology -- is based entirely on utilizing the quantum properties of the incident radiation, it is clear that any radiant energy

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<sup>1</sup>We find it helpful to ask such people, "Explain how an ordinary antenna works using quantum theory." We freely confess our inability to do so!

converter based on utilizing wave properties is in sharp contrast to such cells -- both in theory and physical embodiment. It should not, therefore, be surprising for those familiar with conventional solar cells to at first experience some strangeness when dealing with the newer EWEC concepts.

The idea of extending wave absorption techniques and embodiments well-known in the radio frequency region for signal absorption to the shorter infrared and solar ranges for man-made useful power conversion was first conceived by Bailey [3], as a lengthy literature and two patent searches have revealed.<sup>1</sup> Callahan's significant scientific researches on wave surface interactions on insect antennae<sup>2</sup> later strongly reinforced this concept, and, fortunately, the two became colleagues via the present research grant.

Signal Vs Power Conversion of electromagnetic waves must first be distinguished before explaining the EWEC concept.

In radar, radio, and communications the principal function of the receiving antenna is to convert the incident electromagnetic wave to a useful signal voltage which is then amplified and later heard (radio) or seen (TV). Emphasis is on recovery of the signal. The power conversion

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<sup>1</sup>These are summarized in Chap. 4.

<sup>2</sup>These are summarized in Chap. 5.



efficiency of the antenna<sup>1</sup> is of secondary interest.

In contrast, the power conversion efficiency for an arbitrary radiant energy-electric converter is defined as:

$$\eta = \frac{\text{Useful Output Power}}{\text{Total Radiant Power Impinging On Converter}}$$

The power conversion efficiency,  $\eta$ , is of great importance in radiant energy-electric converters, since it directly determines the required converter area and hence the cost for a given output power. It becomes the absorptivity,  $\alpha$ , when one is dealing with radiant-thermal conversion.

The EWEC Converter is principally intended for radiant-electric power conversion, though we shall see it is also of great theoretical interest and potential value in radiant-thermal conversion.

The Electromagnetic Wave Energy Converter is shown in Fig. 2-1.<sup>2</sup> In Fig. 2-1a the essential elements are seen to be an input radiant energy source having an  $\vec{E}$  field 15 propagating into the converter. The converter consists of absorber elements 16, rectifier 23, filter 24, and load 25

<sup>1</sup>Hence the reason one does not find figures for 'the efficiency of an antenna' in antenna literature. There one is concerned with the 'gain' of a given antenna with respect to a simple dipole, but this is not the same as the power conversion efficiency of the antenna being investigated. Antennas are frequently operated under 'matched impedance' conditions at which point the antenna delivers its maximum power output with load power equal to the power dissipated in the antenna. Because of this signal practice of operating antennas 'matched,' it is popularly but erroneously thought their conversion efficiency cannot exceed 50 percent. An elementary analysis of the Thevenin equivalent circuit shows an antenna array can exceed 50 percent conversion efficiency.

<sup>2</sup>From U. S. Patent 3,760,257, Sept. 18, 1973.

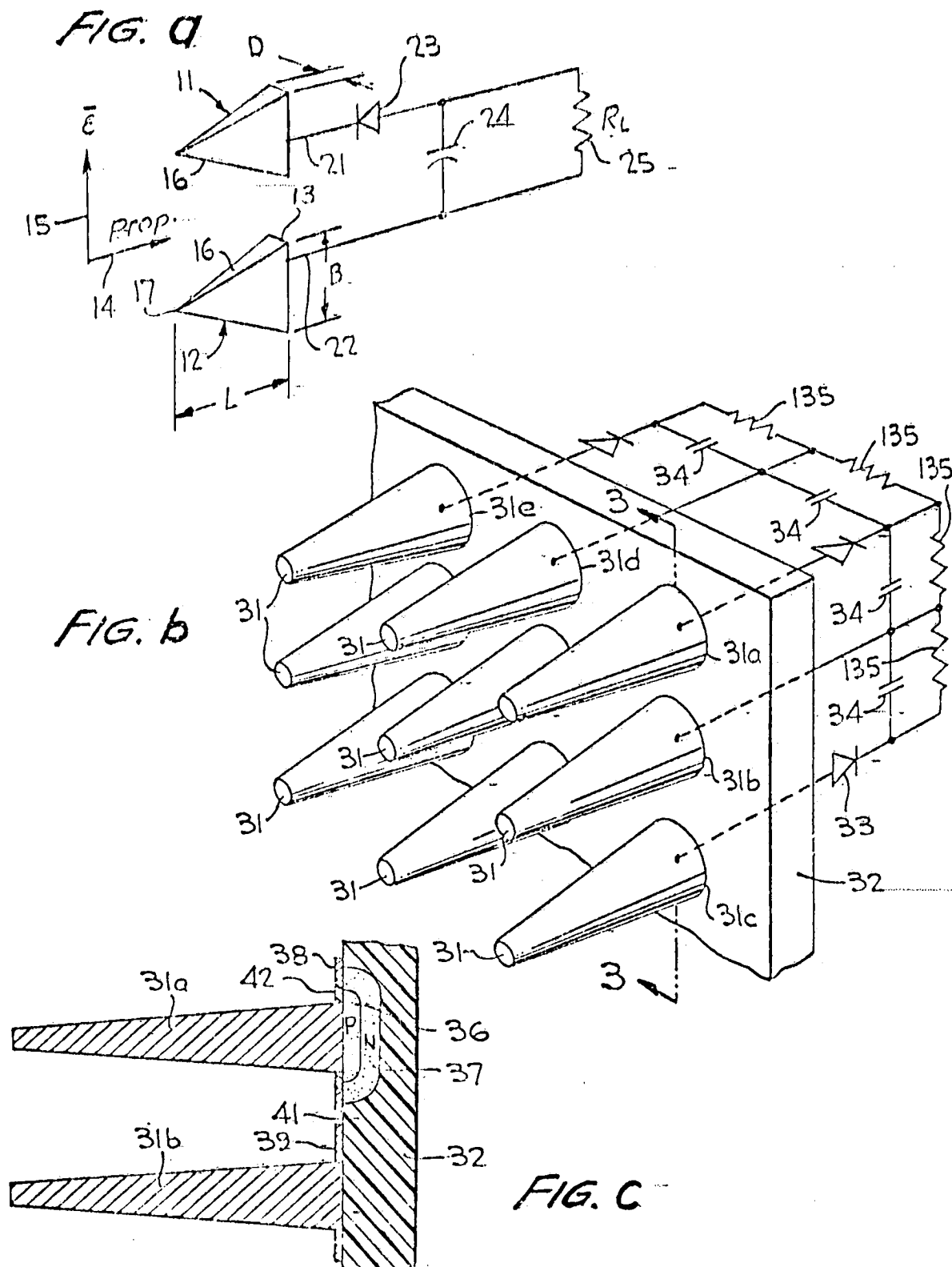


FIG. 2-1 Rough conceptual sketch of new large-area Electromagnetic Wave Energy Converter (EWEC) absorber that might be created. The surface would be rough. It would utilize the wave properties of the impinging radiation. The concept is principally aimed at solar-energy but may also have useful spin-offs for microwave and infrared ranges.

into which we desire useful DC power to appear. The electric field induces currents in the pyramid or cone shaped absorber elements 16 resulting in a voltage between the two absorber elements. It is converted to a DC power by a rectifier-filter arrangement. For short wavelengths, in the IR and solar spectrum range, it is necessary for diode 23 to be physically small with respect to a wavelength so it appears approximately as a lumped constant component. It also ideally would have a small series resistance and large equivalent parallel resistance, thus minimizing power losses.

The absorber elements 16 might be of metal or dielectric materials, depending on whether the converter is to transform to thermal or electric power. For operation in IR and solar spectrum ranges, it is desirable for the elements to be many wavelengths long, principally to give a narrow absorption bandwidth and to permit the structure to be physically built.

By arranging the basic converter of Fig. 2-1a into an array-like structure, we have Fig. 2-1b. Here the wave absorber elements 31 are mounted on a substrate 32 which, in the form shown, is an electrical insulator. It may be rigid or preferably flexible. The converter elements are here shown as lumped constants connected to multiple loads 135. Each pair of absorber elements, e.g. 31a and 31b, and converter elements, e.g. 33 and 34, are seen to be comparable to the elemental system in Fig. 2-1a. The connections are such that for a vertically polarized incident  $\vec{e}$  field load voltages appear in columns of loads 135.

If  $\vec{E}$  is horizontally polarized, then absorber elements 31c and 31d absorb the wave power, convert it in the same way, and feed it to one of the horizontal load resistors.

Thus the embodiment in Fig. 2-1b can convert either vertical or horizontal polarization  $\vec{E}$  fields to useful DC power. If the polarization of  $\vec{E}$  is arbitrary, then it will always have some component in horizontal or vertical directions. These components will be absorbed and converted, capturing all the energy of the incident  $\vec{E}$  field wave regardless of its polarization.

Fig. 2-1c shows an extension of the ideas in Fig. 2-1b. Now the lumped constant elements are replaced by their fabricated microelectronic equivalent, e.g. 36 and 37 from the equivalent of the diode 34 in Fig. 2-1b. Other forms of the rectifier are possible and probably even desirable, e.g. point contact diodes optimized for the spectral range being absorbed.

It is clear that the EWEC makes use of carefully shaped and proportioned structures which microscopically would appear 'rough,' i.e. a forest of small relatively close-spaced conoids or pyramids. Thus this important wave absorption embodiment of EWEC differs markedly from the smooth surface quantum mechanical concepts of conventional solar cells and is generally more like structures found in Nature, e.g. insect antennae<sup>1</sup> and eye retinas in vertebrates.

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<sup>1</sup>See Chap. 5.

The basic technical ideas of this new invention are embodied in Fig. 2-1. For brevity here, many details are omitted. Such embodiments served as the starting point for the present research grant. We expect such embodiments to undergo considerable creative refinement as future EWEC research progresses and our understanding of it grows. Some modification possibilities have already been indicated in [3].

Potential EWEC Advantages are believed to be:

- High Conversion Efficiency In Chap. 9 our elementary analyses indicate that 50 percent or greater efficiency theoretically should be possible, assuming (1) all EWEC absorber elements are the same length, (2) the EWEC absorbers are correctly tuned to the principal incident wavelength, (3) the EWEC converter's bandwidth is 50 percent or more of the irradiating spectral bandwidth, and (4) rectifier and absorber losses are neglected.

Crown's [8] pioneering tests on large area power absorbing 'rectennas' at microwave frequencies had a measured efficiency of 64 percent. No special attempt appears to have been made, however, to optimize the absorber elements as is envisioned both desirable and necessary for EWEC type converters.

So far as we have been able to determine, the EWEC invention is the only new radiant energy-electric converter concept on the contemporary technical scene with a potential -- but yet unproven -- solar conversion efficiency significantly greater than the 24 percent theoretical maximum for solar cells.

- Function Separation Capability appears inherent to the EWEC concept. This means the absorption of the waves are essentially independent from the rectification. Each should therefore be capable of careful modeling and optimization.
- Power Spectrum Matching Capability also appears inherent to EWEC converters. Changing the absorber geometry

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<sup>1</sup>The French have an antenna term, *se coller*, which, loosely translated, means "the wave 'sticks' to the antenna" which more accurately captures the true idea.

by suitable dimensional choices would permit 'matching' the absorbers to the incident power spectrum. Present art semiconductor solar cells are not so conveniently adjustable.

- Control of Absorption Beamwidth pattern would be possible for the first time in solar-electric converters. The beamwidth is the angle of absorptivity at the half power points. By suitable absorber dimensional choices converters could be made with wide or narrow beamwidths to meet the engineering requirements for specific applications. Such control could affect the absorptivity/emissivity ratio and be of considerable importance for an EWEC thermal absorption surface.
- Mechanical Flexibility of such converters also appears inherent if mounted on a suitable flexible substrate. Flexibility has long been a sought for goal in solar cell arrays and applications of solar cells.
- Mass Production Capabilities - eventually.

The extent to which these potential advantages can, in fact, be achieved remains to be seen by future research. We believe the potential advantages great enough that a successful EWEC absorber-converter would have extremely significant long-range commercial importance and value both to the United States and the remainder of the world.

Potential Applications for EWEC converters, when perfected, might include:

#### Radiant-Electric Converters

- Solar Converters for on-site, neighborhood, and central generation of electric power. It is this whole area where a market potential of many billions of dollars exists.
- Microwave Conversion for high power microwave beams to useful electrical power.
- Laser Beam Conversion to useful electric power. Some advanced research in this general area has been discussed by NASA [2] as a means for transmitting bulk

power from earth to space vehicles or vice versa. In either case an efficient absorber-converter of the beam is needed which can handle large power -- of the order of 10 times the sun's intensity.

Radiant-Thermal Converters (By omitting the rectifier)

● Solar Selective Surfaces with high absorptivity/emissivity ratios for use in:

- Δ Solar water heating collectors.
- Δ Solar house heating collectors.
- Δ Solar air-conditioning collectors.
- Δ High temperature flat plate and focussed collectors for solar-thermal-electric generation.

It is too early in EWEC research to have explored these application possibilities in any depth. These, and other applications, will naturally open up when successful EWEC hardware has been created.

Having thus introduced the EWEC concept, in Chap. 3 we deal with the specific goals established for the present research grant aimed at taking the first step toward eventually realizing some or all of EWEC's potential advantages.

### Chapter 3

#### RESEARCH GOALS

Need For Goals. Since this initial grant was of short duration,<sup>1</sup> it was felt vital to have clearly established goals at the beginning to maximize the program's benefit-to-cost ratio. The following goals and rationale were established as guidelines.

Research Goal: To study the absorbers on the EWEC invention and attempt to quantitatively determine their theoretical feasibility at microwave and micrometer wavelengths.

No experimental work was to be done, it being felt more essential to first strengthen the scientific base for the EWEC concept, particularly the key absorber elements.

It is important to realize it was not the goal of this initial short research effort to examine the scientific and engineering feasibility of the entire invention -- absorbers, rectification, fabrication, and a multitude of other significant areas. Research for these could be undertaken later. All these principal problem areas have been specifically recognized, identified, and tabulated; but then it is not possible to deal with all the problems simultaneously. Instead we chose to focus on one of the most important fundamental areas.

Research Focus: Absorbers Our principal reasons for choosing to focus the research on the EWEC absorbers were:

<sup>1</sup>The grant was for only 6 months of part-time work under austere funding conditions.



- They are one of the principal elements of the invention. Without them the invention is useless.
- The least is known about such absorbers of any element used in the invention. Considerably more precise scientific and engineering knowledge is needed before practical converters can be designed with assurance they will work.
- Knowledge learned about absorbers probably would have useful spin-offs to other areas, e.g. solar thermal absorbers for terrestrial and space use. There was a preliminary indication that better radiant-thermal absorbers could be made by not just 'roughing up' the surface, as is now done with some solar thermal absorber surfaces, but by causing the surface to have a coating of uniform height cones or tetra-hedra appropriately arrayed.

An additional spin-off could accrue to the agriculture area of insect control. The better understanding of absorbers from this research was recognized as directly applicable to insect antennae and, in addition to advancing science in that area, could -- perhaps eventually -- lead to super efficient electronic means of trapping insects, preventing crop and food destruction.

- If initial research attention were focussed on the diode converters, there is little assurance that such research alone when successfully completed could lead conclusively to the feasibility of the EWEC invention. We do not minimize the importance or difficulty of the rectification problem on EWEC, for it alone is a formidable technical problem. But we knew much information already existed regarding equivalent circuits, parameter values, power conversion efficiency, etc. of diodes, particularly the works of Brown [9], Javan [43], Van der Ziel [75] and others.

There were also other reasons for focussing this short research program on absorbers.

In this early theoretical work it was felt essential to deal only with simple plane polarized monochromatic electromagnetic waves. The non-coherent, wide spectrum, stochastic amplitude, randomly polarized wave case -- ultimately needed for full theoretical understanding of -- successful solar-electric EWEC converters -- was recognized as theoretically too complex a starting point.

At The End of the research program it was hoped we would know about the EWEC absorbers:

- Material - - - Whether metal or dielectric is best.
- Geometry - - - Approximate ranges -- in terms of wavelengths -- it must theoretically be for efficient power absorption. Also whether conical or tetrahedron is best and whether solid or thin wall dielectric is best.
- Losses - - - About what to expect. These would be related to the number of wavelengths the absorber is long.
- Center Freq. - - - About how to predict it for an optimum absorber and how it is related to the absorber geometry.
- Bandwidth - - - About what it should theoretically be. Particularly the fractional bandwidth is a crucial factor for a later solar-electric converter.
- Beamwidth - - - Some preliminary indication (sharp or broad) of what it might be, recognizing later supportive experimental work would be needed.
- Array Spacings - - - Probably know one that theory indicates should work. Time would not permit exploring other possible refinements, as log-periodic spacings, in such a short R & D program.
- Conversion Efficiency - Should know the theoretical upper conversion efficiency for an EWEC absorber driving a resistive load when irradiated with a plane polarized electromagnetic wave.

Overall, our intent would be to learn the most about theoretical aspects of EWEC in the shortest possible time -- hence minimum cost to NASA. Care was to be exercised to choose theoretical EWEC absorbers (or arrays of such elements) with a high likelihood of later usefulness for the solar and laser ranges (infrared) and with some regard for ultimate

manufacturability.

The General Research Plan for achieving the above goals was to first "learn from Nature" what are probably the best absorber element materials and morphology, particularly based on the pioneering work of Callahan on insect dielectric antennae. Simultaneously we sought to identify, collect, study, and summarize relevant scientific and engineering papers, particularly on the physics of electromagnetic wave-surface interactions which subject appeared shrouded in mystery and empiricism among scientists, solar engineers, and ourselves.

Finally, it was hoped that with such insights accumulated it would then be possible to make a first attempt at modeling EWEC type absorbers. Then, and only then, could a theoretical analysis be performed, starting from Maxwell's equations.

We summarize our results of the first part of this general plan in Chap. 4. Subsequent Chaps. elucidate our results from the remainder of the plan.

## Chapter 4

### PRIOR RESEARCH ON WAVE-SURFACE INTERACTIONS

Introduction Prior research on electromagnetic wave-surface interactions specifically aimed at creating a direct solar-electric converter appears to have not been done except by Bailey; nor has any previous systematic attempt been made to collect and organize scientific and engineering publications thereto.

This Chap. allows readers to interact with references relevant to the understanding and ultimate solution of the complex electro-physics problem of electromagnetic waves interacting with surfaces rough in comparison with a free-space-wavelength, i.e. having a character similar to that proposed for EWEC.

Works in major areas of importance to EWEC research are here arranged and summarized by loose categories. Other arrangements are, of course, possible. Other relevant references are cited throughout this report.

The Earliest Writing found on wave-surface interactions relevant to EWEC was by Lord Rayleigh [64], circa 1897, who worked out some of the mathematical physics of electromagnetic waves in dielectric cylinders.

Physicists prior to that time had, of course, addressed the more general problem of the wave-like nature of light as first advanced by the Dutch Physicist Huygens (1629-1695)..

Brief History Of EWEC Bailey [4] in 1968, while at Goddard Space Flight Center exploring the possibilities for creating a major state-of-the-art improvement in direct radiant-electric conversion technology,

invented EWEC. The following summer experimental verification of the basic metallic absorber structure was made at the University of Florida. These tests were conducted in the UHF microwave range.

He first published [3] the concept in 1972, followed in 1973 by an elaboration of these ideas [2]. Fortunately, about this time Bailey and Callahan became colleagues, and a great similarity was seen between Callahan's previous pioneering work on insect antennae and Bailey's ideas regarding EWEC.

After several years of patent work involving 'the rights' question, NASA filed for a U. S. Patent on EWEC which issued in 1973 [1].

The present NASA grant, resulting from a 1974 proposal, enabled this advanced research to go forward. Thus from the time the invention was first made (1968) until serious scientific and engineering research commenced (1975) was nearly seven years.

EWEC-Related Patents Mueller [58] relates in his patent an invention of centimetric antennas and particularly of end-on high gain directive dielectric antennas. He discusses shape of rods, directivity and gain.

Southworth [69] discusses the use of a multiunit end-fire array of rods of dielectric material resulting in a directivity principally along their axes. His invention was for microwave radio antenna systems.

Somewhat similar ideas at much shorter wavelengths are looked at in EWEC research.

The above two patents appear to be the closest to the EWEC invention revealed from two patent searches; but neither anticipates

operation in the solar range, and neither is intended principally as a radiant energy to power converter as EWEC.

Waves And Insects -- By Others Than Callahan Hsiao, et. al. [41] have also investigated the possibility that insects communicate by coherent electromagnetic waves. They point to Callahan's [19, 20, 21, 23, 24, 25] pioneering work in this area and discuss many points in their common research of the question. They conclude there is some possibility in this method of communication between insects, but point out continuing research will show more concrete conclusions.

Eye-Like Structures And Visual Cells Bernhard [7] conducted experiments on large models of conical protuberances and nipples illuminated by microwaves and discusses similar structures found in Nature.

Clapham and Hutley [29] reported on the suppression of wave reflection from surfaces covered in a regular array of conical protuberances in a manner similar to that observed on the corneal lenses of the moth. They substantiated Bernhard's theory of suppression through a graded transition of refractive index between the air and the cornea by measurements with microwave radiation reflected from a scaled-up model.

Bernard et al [6] later studied the eye in light of antenna theory and found a counterpart to many communication engineering type structures existing there. They explain light interaction with the surface of the eye from a wave approach.

A detailed discussion of research of visual cells is presented by Young [78]. He clearly shows the structures, rods, and cones found in humans and animals are similar in morphology to the EWEC dielectric

model we present herein in Chap. 7.

IBM Work Cuomo, et al. [31] have accomplished recent highly significant research into surface treatments for high temperature solar-thermal absorbers. They demonstrate the excellent absorber capabilities a special tungsten surface has operating in the solar spectrum from about 0.5 to 40 $\mu$ m. They claim an absorptivity of 96 percent for it. They attribute the high absorptivity to varied population of spearlike structures called dendrites, large and small, on varied spacings. This surface structure closely parallels the application of the EWEC-like metal structure discussed in Chap. 6 and our two-length model, Fig. 9-8. Tailoring the surface for absorption of various frequencies is experimentally achieved by altering the height-to-width ratio of the dendrites, much as discussed for EWEC.

Australian Work Thornton [72] shows that a material surface configuration can be optimized for best thermal absorption and lowest emissivity. He investigates a corrugated surface formed by cutting rectangular slots in it. Bandwidth was investigated and optimized for multilayer surfaces. References are made to the moth's eye principle of reduction of reflection on an array of very fine tapered cylindrical protuberances.

Japanese Work Tani [71] reports a project of solar energy power systems. Deposit meshes, thin films, and horns made from metal and semiconductor material absorb sunlight electromagnetic energy and produce high temperature thermal energy. They have applied for several patents in this field. Technical details on this work are not available.

Rough Surface Solar Cells The concept of deliberately roughening the surface of conventional solar cells is believed to have been first explored by Bailey [4].

Haynos et al [39] of Comsat Laboratories later described a surface treatment of the conventional solar cell where a myriad of tetrahedral (EWEC-like structures) were used to promote multiple interactions between the surface and the light, thereby reducing reflection losses markedly and increasing the cell efficiency to a high of 15 percent.

Rough Solar-Thermal Absorber Surfaces Peake [60] has indicated the similarity to EWEC of surface structures of a high absorptivity ( $\sim 0.91$ ) paint used by NASA. He showed SEM photographs of the paint surface showing an EWEC-like structure with random height cones.

Santala [66] states that an intermetallic compound such as  $\text{Fe}_2\text{Al}_5$  having a highly porous surface structure provides a surface that absorbs as black body cavities if the pore structure is of the same order as the wavelength of the solar radiation. However, it radiates in the infrared wavelength region as a flat surface. An Aluminum-Nickel compound had the best qualities of compounds studied and was selected for optimization.

Solar Selective Coatings Koltun [47] (USSR) describes a selective coating which makes it possible to change the absorption coefficient  $\alpha$  of solar radiation and, simultaneously, the degree of blackness  $\epsilon$  over wide ranges.

Seraphin [67] discusses selective solar coatings using chemical vapor techniques for deposition of  $2\mu\text{m}$  thick silicon films of satis-



factory optical quality onto a metallized substrate. The system can be used to transform solar radiation into high temperatures. Such surfaces, while structurally dissimilar to EWEC-like surfaces, are based on well-known optical wave interference effects and, somewhat like EWEC, exhibit a wavelength selectivity.

Antennas And Waves Childers [27] explained some theoretical ideas concerning antenna reception of nonisotropic stochastic fields. Antennas are treated from the combined viewpoint of the theory of statistical communications, antenna theory, and the theory of optics. His ideas appear potentially useful to future EWEC research recommended in Chap. 12.

Microwave Absorbing Structures Emerson and Cumming's catalog from their Microwave Products Division [81] presents a wide variety of well-known microwave absorbers and absorber materials that are clearly EWEC type construction. They use pyramidal or conical structures to form anechoic surfaces which insure minimum reflected energy in a microwave test chamber. The cone lengths must be sized to the frequency range being used -- long cones for long wavelengths and short ones for short wavelengths.

Monomolecular Layers And Light In an article by Drexhage [34], multi-layer systems of long-chain fatty-acid molecules and fluorescent dye molecules were used to study the structure of light waves, revealing a close analogy between a radio antenna and a light-emitting molecule.

Wave-Surface Interactions On Metal Surfaces of Various Geometries

Cherepanov [28] (USSR) has investigated the absorptivity of a spiky

surface of a structure similar to an EWEC absorber. However, the system he proposed is as a plane-layer-radio-absorber material, operating at much longer wavelengths than EWEC.

Ornstein, et al, [59], Sinor [68], and Lee [48] discuss the wave-surface interaction on corrugated conducting surfaces and is relevant to the solution of the EWEC models proposed in Chap. 6.

Scattering from perfectly conducting sinusoidal surfaces is discussed by Millar [53, 54, 55, 56], Fang [35], Zaki, et al [79, 80]. They outline methods of solution to scattering from this type periodic structure.

It is interesting to observe there is a large body of mathematical physics literature dealing with scattering of electromagnetic waves, of which the above is but a sample, from various surfaces. Substantially less deals with wave absorption.

Dielectric Materials As Antennae and Waveguides are discussed by Di Domenico [33], Mueller et al. [57], Kiley [46], and McKinney [51]. Optimum dielectric rod and tube dimensions, bandwidth, gain, attenuation, propagation and many other topics of interest are presented which strongly relate to EWEC research. The most current reference [33] compares losses in dielectric material with other electromagnetic wave propagation media -- a result used in Chap. 8.

Wave-Surface Interactions On Dielectric Surfaces Scattering from a dielectric wedge shaped structure is discussed by Mahan et al [49] and is related to EWEC dielectric models of Chap. 7.

The theory of scattering by finite dielectric needles illuminated

parallel to their axes is discussed by Rawson [62]. A derivation of the angular distribution of light scattered by the dielectric needles of radius  $r \ll \lambda$  and a finite length  $L \gg \lambda$  is presented. This theory was developed to help interpret measured scattered-light distributions from low-loss optical-fiber waveguides.

Scattering from an infinite long fiber circular cylinder at oblique incidence was presented by Kerker [45]. He reports such computations suggest possibilities for improving the technique for estimating fiber radii.

General Solution Methods Beckman et al [5], Davies [32], Harrington [38], Ikuno et al. [42], Meecham [52], and Wilton et al. [77] show some significant and perhaps promising methods for the later analytical solution of the rough surface models proposed in this report.

Rectification Near Visible Light Wavelengths has been preliminarily dealt with by Matarrese [50], Twu [74], Small [70], and Twu et al. [73]. Using conventional long-wire antenna theory [50, 70, 73, 74] and thin film micro-electronic depositing techniques [70] they were able to demonstrate rectification to  $10.6\mu\text{m}$ , broad-band characteristics from radio and microwave frequencies (10Ghz) to the infrared region ( $10.6\mu\text{m}$ ), and forming diode-antenna elements into linear phased arrays. The authors point up many possibilities using these techniques for improving the diode's rectification properties at these wavelengths.

In Summary, it is evident a sizeable technical literature exists in the general area of the physics of electromagnetic wave-surface

interactions. Some of this literature was only sampled for lack of time, e.g. the entire antenna field is obviously relevant in a general way even though antenna theorists do not generally consider 'surfaces' of antennas; but various arrays approach this concept.

The scattering of electromagnetic waves from mountains, knife edges, periodic surfaces, random surfaces (e.g. the ocean), and other surface geometries have all been extensively studied; but comparatively little technical effort appears to have been devoted to the interesting and potentially useful theoretical problem of absorption maximization of electromagnetic waves by the surface as needed for EWEC solar-thermal surfaces. The Australian work by Thornton [72] appears to come closest to the EWEC invention in this regard.

Though, in toto, these prior-art publications look at various parts of the problem of wave-surface interactions, no reference was found which envisioned the EWEC embodiment in the form invented by Bailey [1].

From this literature survey, which we interpret as strengthening the scientific base for the EWEC invention in numerous ways, we now see a broader picture of rough metallic surfaces and rough dielectric surfaces as sub-parts of a continuum of the larger area of wave-surface electro-physics. Further, we see these theoretically linked by the commonality of the incident waves inducing currents, though the internal field distributions naturally are different for the two cases. Finally, and very importantly, they are linked morphologically. These, and other linkages, appear to have not been previously recognized, as we indicate in Chap. 10.

## Chapter 5

### EWEC ABSORBERS ON INSECTS

Relevance Of Insects And EWEC Callahan, a research entomologist, has methodically investigated insects and their communication and navigation systems for about 20 years [26, 25, 24, 23, 22, 21, 20, 19, 18, 17, 16, 15, 14, 13, 12, 11, 10], and in particular the antennae found on various insects. His most recent research on the Fire Ant Antenna is in Appendix I. The results of the impressive body of scientific knowledge can only be briefly summarized here, unfortunately, for it is a fascinating story of general interest to scientists and engineers. An extremely readable summary of his life's research in this field is in [10]. A shorter scientific version is [11], and an even shorter one is [12]. This research is all highly relevant to current EWEC R&D, though one might initially wonder how insects and energy conversion are related.

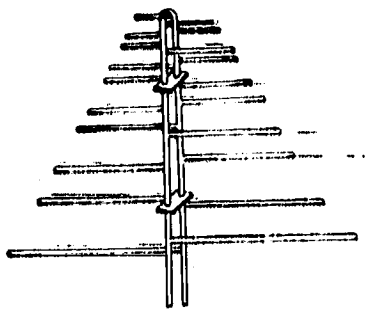
In summary, Callahan's theories and scientific research have shown -- and been generally proven beyond reasonable doubt in our mind -- that:

- Insects communicate and navigate by means of electromagnetic waves -- in addition to visual means which we do not consider here.
- The wavelengths used are in the infrared range (from about 1 $\mu$ m to 30 $\mu$ m) with principal channels occurring within the 7-14 $\mu$ m atmospheric 'window' and the 17 $\mu$ m and 25 $\mu$ m 'mini-windows.'
- The radiation emitters are: (1) sex scents called pheromones which emit high amplitude IR narrow band maser-like emissions, and (2) broad band black body radiation from the insect's body. The latter radiation is modulated by

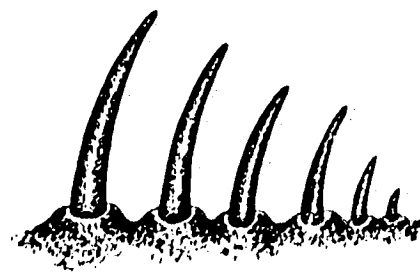
the vibration of the insect's wings and is used in navigation for both 'target'-identification and azimuth orientation.

- The pheromone is given off by glands in the female.
- Wind carries the pheromone into the atmosphere -- a variable density gas.. Sunlight or night sky irradiation causes the pheromone-molecules to emit narrow band high amplitude IR electromagnetic waves....
- The radiated waves are received -- afar or near -- by the antennae of the male which follows the trail of the emitting gas pheromone to its source -- the female..
- Insects have large numbers of receiving antennae, called spines or sensilla, of various kinds<sup>1</sup> and lengths (in the range of about 2 $\mu$ m to 200 $\mu$ m, depending on insect specie). Different length spines respond to different IR wavelengths. The nerve output of a spine connects directly with the insect's brain..
- The principal antenna elements are a type of open resonator -- as are all antennas -- known as a dielectric antenna. The various kinds found on insects have been identified, classified, and dimensionally measured on some insects..
- Insect dielectric antenna elements are arranged in elaborate arrays.. There is a strong correspondence between the shape, form, and arrangement of arrays observed on insects and known man-made antenna arrays, e.g. arrays of vertical antennas above a ground plane.
- By means of the modern scanning electron microscope (SEM) high resolution photographs can be taken of the details of these microscopic receptors of electromagnetic waves found on insects. The SEM is the principal research tool for observations, and a high resolution Fourier analysis interferometer spectrophotometer is the principal tool for emission measurements.
- The entire scientific research area of insect communication and navigation via electromagnetic waves is presently in a

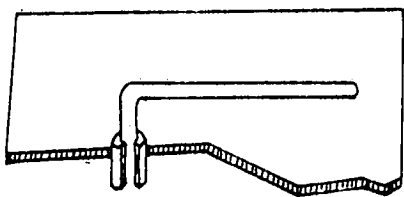
<sup>1</sup>Virtually any kind of antenna form created by man to date can be found on insects. A few examples are shown in Figs. 5-1 and 5-2. Other types, not man-made to date, have also been observed on insects.



**A**

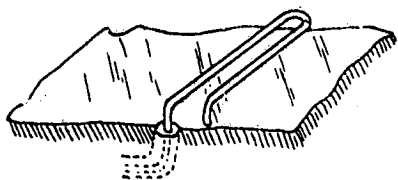


LOC-PERIODIC



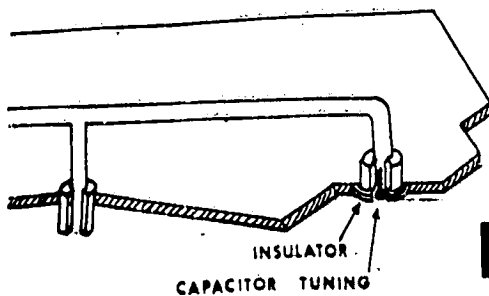
**B**

STUB BENT



**C**

SICKLE SHAPE



**D**

LOOP

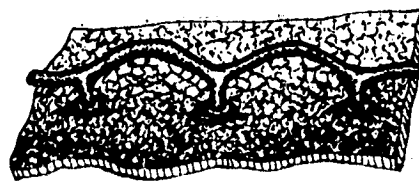
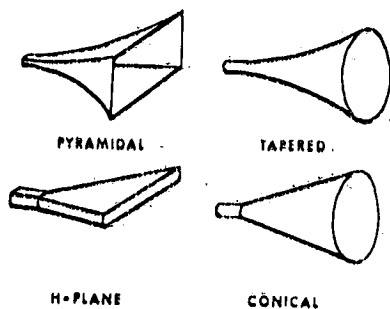


FIG. 5-1 Types of man-made metal antenna (left) and their insect dielectric counterpart (right).

# HORN, PIT & HELICAL ANTENNA

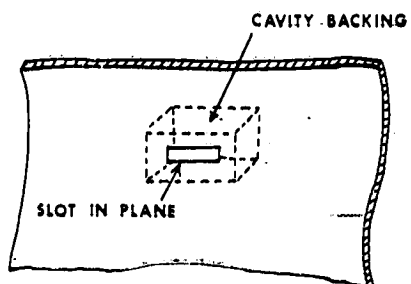
RECTANGULAR HORNS

CIRCULAR HORNS



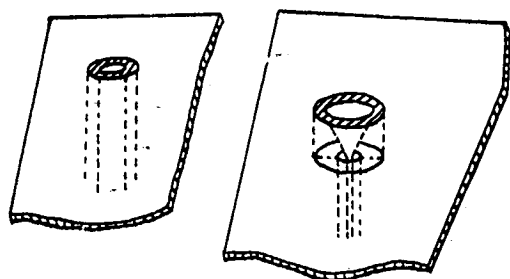
A

HORN



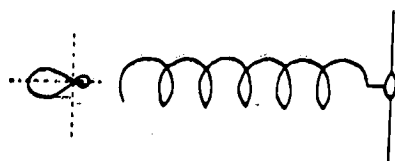
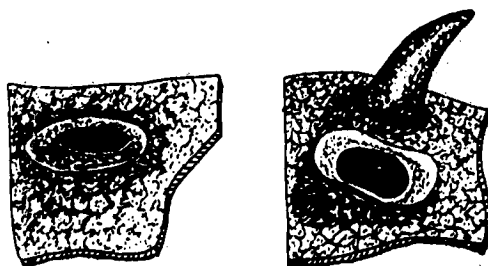
B

CAVITY SLOT



C

CAVITY PIT



D

HELICAL

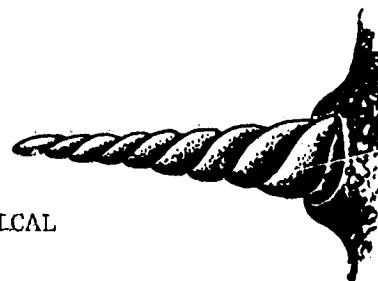


FIG. 5-2 Types of man-made metal antenna (left) and their insect counterpart (right).



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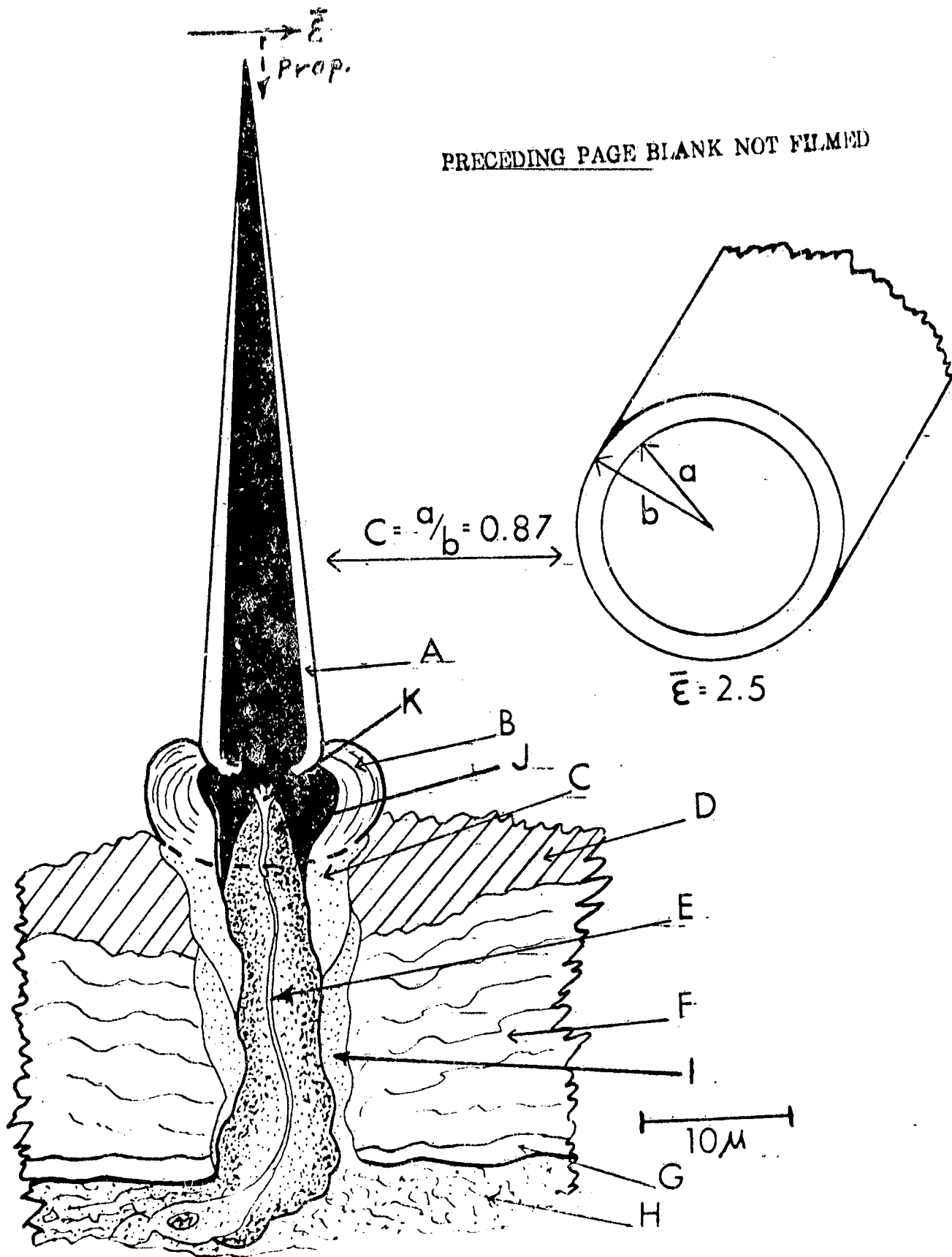


FIG. 5-3 Callahan's original sketch [20] for moth (Saturindae) "dielectric waveguide spine."

measurements of 14 spines on night-flying moths (saturnidae). As many as 150-200 such spines may be present in a group on the cecropia moth. He earlier postulated in 1965 [23] and 1967 [21] that such spines may act as polytubular dielectric waveguide antennae in various spectral regions.

We now examine Fig. 5-3 in some detail and propose some new theories about how such wave absorbers probably work in light of modern electro-optics. These are based on extending Callahan's earlier astute observations. There are many subtleties in this exquisitely structured sensilla -- subtleties which took us considerable time to recognize. Once recognized and explained, they are quite simple to those familiar with electromagnetic fields and waves. We examine the ensemble of Fig. 5-3 first and then each part separately.

- Overall The sensilla consists of a tapered Spine A positioned above a probe K and its nerve output which goes directly to the insect's brain. The incoming  $\vec{E}$  field propagates into the spine from the direction shown for maximum nerve response. The spine focusses the arriving  $\vec{E}$  field on the probe K.

Spine A is supported by a doughnut shaped material B above a more-or-less uniform surface D -- the insect's epicuticle. Subsurface materials F -- the exocuticle -- and H -- the epithelium layer -- complete its lower parts.

- Spine A is believed made of a dielectric material. It is a tapered conic with walls so thin they are transparent in SEM photomicrographs.

Kiely's [46] experiments at microwave frequencies on dielectric antenna show that tapering decreases the antenna pattern side lobes markedly, resulting in a single main lobe centered on the conic axis. Further, it is well-known in electromagnetic field theory and in microwave hardware that to transition from one field region to another with

minimum reflected wave power -- hence maximum transmitted power -- the wave guiding structure should be tapered over several wavelengths, affording a slow transition of guide impedance for the wave from one medium to another. Thus from the wave viewpoint an array of such tapered spines found on insects appears to have precisely the optimal shape for maximum absorptivity of the EM wave.

The material -- if any -- inside the spine is not known. Kiley's work [46] on hollow dielectric cylinders indicates that making the walls thin, e.g.  $a/b = 0.87$ , results in the lowest dielectric attenuation loss/meter in the direction of wave propagation. It can easily be shown analytically that the hollow tapered spine structure of Fig. 5-2 has  $a/b = \text{constant}$  throughout its length and therefore presumably is of minimum loss.<sup>1</sup>

The spine length averages about  $66\mu\text{m}$  long with a base diameter of  $6.57\mu\text{m}$  for the cecropia moth.<sup>2</sup> In terms of the more fundamental guide length to free space wavelength, spines are about 2-6 wavelengths long on insects. Thus such insect wave absorber structures in Nature are many wavelengths long. Similar many wavelength structures are well-known in antenna engineering as rhombic antennas, end-fire arrays, and others -- all tending toward high directivity to an incoming EM wave. Thus, for the insect, the fact that his sensillae are many wavelengths long increases his directional sensitivity. Arrays of such dielectric sensillae further increase his antenna pattern directivity. Finally, making the array pointable in an arbitrary direction by a controllable support structure permits the insect to 'see' electromagnetically in the direction of the array's principal lobe.

If a given  $4\lambda$  long dielectric spine is receiving an EM wave, elementary antenna theory indicates it should also be receptive to other eigenvalue wavelengths multiply related. This important intriguing theoretical problem remains to be analytically solved for tapered thin-walled dielectric wave absorbers. The net effect, undoubtedly, is to increase the insect's effective band width 'seen' of the electromagnetic spectrum.

<sup>1</sup> Attenuation losses will be treated more quantitatively in Chap. 8

<sup>2</sup> As stated earlier, however, the length and diameter varies with insect species.

● — The Lower End Of Spine A, Fig. 5-3, is gently curved inward toward the probe K. It would appear that curving permits the small portion of the incident wave which is trapped in the thin-wall spine A and propagating downward and reflecting from the inner and outer spine surfaces to exit the spine in a direction neatly aimed at the probe K. Such EM energy is probably a small portion of the total arriving at K, the major part arriving directly at K through the focusing of spine A; but it is interesting to observe that the probable smaller portion propagating out the end of spine A is not wasted in Nature's design.

● — The Probe K is located on the spine's geometrical axis and in a position to capture most of the incident EM wave focussed on it. The probe is composed of four elements arranged as well-known V-antennas. Each element of the probe has a short length; i.e. it is either an appreciable fractional portion of a wavelength or, at most, a few wavelengths long; precise measurements have not been made on probes alone.

We have reason to believe the probe elements are composed of long-chain organic molecules, each chain acting like the classical thin wire-antenna, the result being a composite receiving antenna pattern for the probe which suitably 'matches' the EM radiation arriving above from spine A.

We also have some indication that were the probe geometry alone more carefully examined than has been done to date, it would be found to be a circular solid of revolution with cross section shown in Fig. 5-3. If later SEM studies show this true, we anticipate the obvious implication that the spine-probe system could receive E fields of arbitrary polarization angles measured at right angles to the propagation direction. It would thus appear the insect sensilla neatly and beautifully simply solves the arbitrary polarization problem inherent in solar radiation by means of its circular geometry.

The probe's output is obviously coupled into the nerve E. The precise internal mechanism for how the received voltage on the probe elements, which is at IR wavelengths, is converted to an electrical signal on insects is not known at this time. Such research knowledge would have obvious implications for the later design of any man-made rectifier -- another opportunity to 'learn from Nature.'

● Spine Support B physically holds the spine A in suitable position with respect to probe K. Ideally the support should be lossless and reflectionless so that any signal propagating in it would not be reflected to phase add or subtract from the principal arriving EM signal wave, thereby distorting the signal 'seen' by the insect.

Note that spine A has been delicately placed into B at such a location, as ray optics shows, to minimize the field's entering B and propagating downward through the material B. Further there is only a small area of contact between the two which should minimize the transmitted wave into B even more; but a small  $\vec{E}$  field would enter B. Material B could be -- and probably is -- a lossy dielectric which begins to dissipate the wave propagating downward through it.

● Transitioning Impedance C and I. The small portion of the  $\vec{E}$  field that gets into B then enters the circular cylinder material C which is neatly tapered on its lower end. Thus material C appears to be a transitioning impedance between B and I. If material B has an intrinsic impedance  $Z_B$  to the downward propagating wave, material C has  $Z_C$ , and material I has  $Z_I$  then, material B probably obeys the well-known relation [61] for matching sections:

$$Z_C = \sqrt{Z_B Z_I}.$$

Similarly material I matches to the internal impedance of layer H according to:

$$Z_I = \sqrt{Z_C Z_H}.$$

It thus appears, that when interpreted in the light of classical electromagnetic waves and waveguide theory, the spine support structure on insects consists of two carefully designed transitioning impedances which aid in matching the free space impedance to material H with minimum reflections and interference with the principal received signal 'seen' by probe K.

● The Cavity Around Probe K Note that Fig. 5-3 clearly shows a cavity around the probe formed of the outer surface of the probe support material J and the inner surface of B. Further, we note that the lower portion of the cavity is tapered.

It thus appears the probe cavity is marvelously

structured, as classical ray optical methods again show, so that any portion of the EM wave which misses probe K is neatly absorbed in the tapered structure materials below or in the outer surface of material J -- which is probably a lossy material -- where it is dissipated.

- Spine Surrounding Surface/Subsurface An incident EM wave propagating downward but outside the spine strikes layer D and propagates through F into H where it remains dissipated. It thus appears that outside the spine region there are two layer type transitioning impedances to minimize wave reflections from Nature's 'ground plane' on the insect.

Such plane wave signals arriving outside the spine naturally contribute nothing to the insect's probe K output. There is growing research evidence that the insect may use these waxy layers for other purposes, as measuring temperature, humidity, atmospheric charge, and other environmental parameters. These, though scientifically interesting, seem less relevant at this time to EWEC R&D than the sensilla.

Conclusion. It is evident from this brief new research investigation of insect spine morphology that such structures found in great numbers on insects are marvelous electro-optic structures. Should our theoretical explanations revealed here for the first time of how an insect's dielectric sensilla probably works prove valid in later research, as we believe they will be, then it is clear that the lowly insects give us very strong clues -- if we correctly interpret them -- for designing successful large area man-made electromagnetic wave converters for power purposes. Insect signal converters appear to have been working in the IR range on a grand scale in the insect world for untold time heretofore. As is evident, more scientific research into the whole insect sensilla would obviously strengthen and enlarge the theory advanced above.

In Chaps. 6 and 7 we show our first formulations of the theoretical model for man-made EWEC converters, based on our insights -- recognized as not fully complete -- learned from insect sensilla research.

THEORETICAL EWEC MODEL -- METAL ABSORBERS

Two Absorber Material Class possibilities exist for EWEC converters:

1. Metals Bailey's first EWEC test model at microwave frequencies was copper [3]. Virtually all practical antennas in use today are metal or involve electromagnetic fields impinging on metal.

Nearly all known practical solar thermal absorbers, excluding plastics and solar ponds, in use today in the growing solar energy utilization field are of metal. There are numerous empirically determined surface treatments for enhancing solar energy absorptivity of metal surfaces, e.g. roughening, etching, thin film selective surfaces, and others.

Cumo's recent success [31] in constructing a 96 percent absorptivity solar thermal surface was of an EWEC-like structure made of metal.

The idea of capturing the sun's energy via selective surfaces arranged in V grooves on metal appears at least as old as 1909 [36]. This idea of periodically grooving metal surfaces is reasonably well-known, but not widely applied, among solar absorber researchers and engineers.

The detailed physics of wave surface interactions for all the above metallic embodiments appear not well understood at this time.

Chap. 4 cites some previous investigations of wave-surface interactions on metal surfaces of various geometry.

2. Dielectric materials for EWEC absorber elements are strongly suggested by the insect antennae, Chap. 5. Also, Bernard and Miller [6] have shown that insect eyes contain numerous dielectric cones and nipples as optical waveguides.

The use of various dielectric materials is well-known in applied optics, e.g. 'light pipes.'

Dielectric antennas, though not well-known among electrical engineers, constitutes an identifiable area where dielectric materials have been successfully used for receiving electromagnetic waves. The idea of dielectric cylinders supporting electromagnetic waves is at least as



old as 1897 and Lord Rayleigh [64] who worked out some of the early mathematical physics.

Commercially available EWEC-like structure material [81] has been used many years as microwave absorbers in antenna and microwave systems engineering. Such materials are lossy dielectrics.

Scattering of EM waves from dielectric cylinders [76] [44], wedges [49] and bodies of arbitrary cross section [77] have been reported. Though our principal interest here is absorbing EM waves, scattering is obviously related.

Chap. 4 cites previous investigations of wave-surface interactions on dielectric surfaces.

Importance Of Material Type Determination of the type of absorber material to be used on EWEC converters is obviously a key research problem having immediate theoretical importance and later design implications. Clearly the materials technology for creating large area metallic whiskered surfaces is not likely to be the same as if the surfaces were thin walled dielectric whiskers.

Finally, there is the important matter of the intended function an EWEC surface is to perform. An EWEC solar-thermal absorber might best be made of metal where the impinging EM wave power is dissipated throughout the surface of the absorber as heat and then conducted into the metal volume whereas a solar-electric EWEC converter might require a dielectric material with minimum losses in the EWEC absorbers proper.

Only after proper modeling and analytics have been done can rational choices of metals vs dielectrics be made.

Modeling Rationale We early recognized formulating the explicit theoretical metal model case would be somewhat different from the model for the dielectric case. We chose to formulate the simpler metal case first.

We have long recognized the theoretical difficulties inherent in dealing with the more complex 3-dimensional case. We felt most progress could be made in this initial theoretical work by first studying the 2-D case. Accordingly we chose to make both principal models 2-D to simplify the ~~later~~ analytics.

Thus this Chap. presents our theoretical EWEC model for metals. Chapter 7 presents our similar model for dielectric materials. We present the models succinctly, clearly cite necessary assumptions, indicate specific analytical goals, and briefly justify the model ~~and~~ our choices. Completion of these then defines the major theoretical technical problems resulting from the present research grant. They are thus set up suitable for later analytical attack.

Problem Formulation: EWEC Absorber - Metal Case

The Proposed Model is shown in Figs. 6-1 and 2. The incident wave, with  $\vec{e}$  field in the x direction, propagates in the negative z direction into metallic EWEC absorbers  $A_1$  and  $A_2$  which extend to  $\pm\infty$ . Each has electrical conductivity  $\sigma$ . A load resistor  $R_L$  ohms/meter connects adjacent absorber faces as shown. Pertinent geometric design parameters are indicated.

Assumptions To Be Made are:

● Incident Wave

- Δ Uniform plane wave
- Δ Linearly polarized as shown
- Δ Continuous -- no modulation, constant amplitude
- Δ Coherent -- constant phase
- Δ Monochromatic with power spectral density

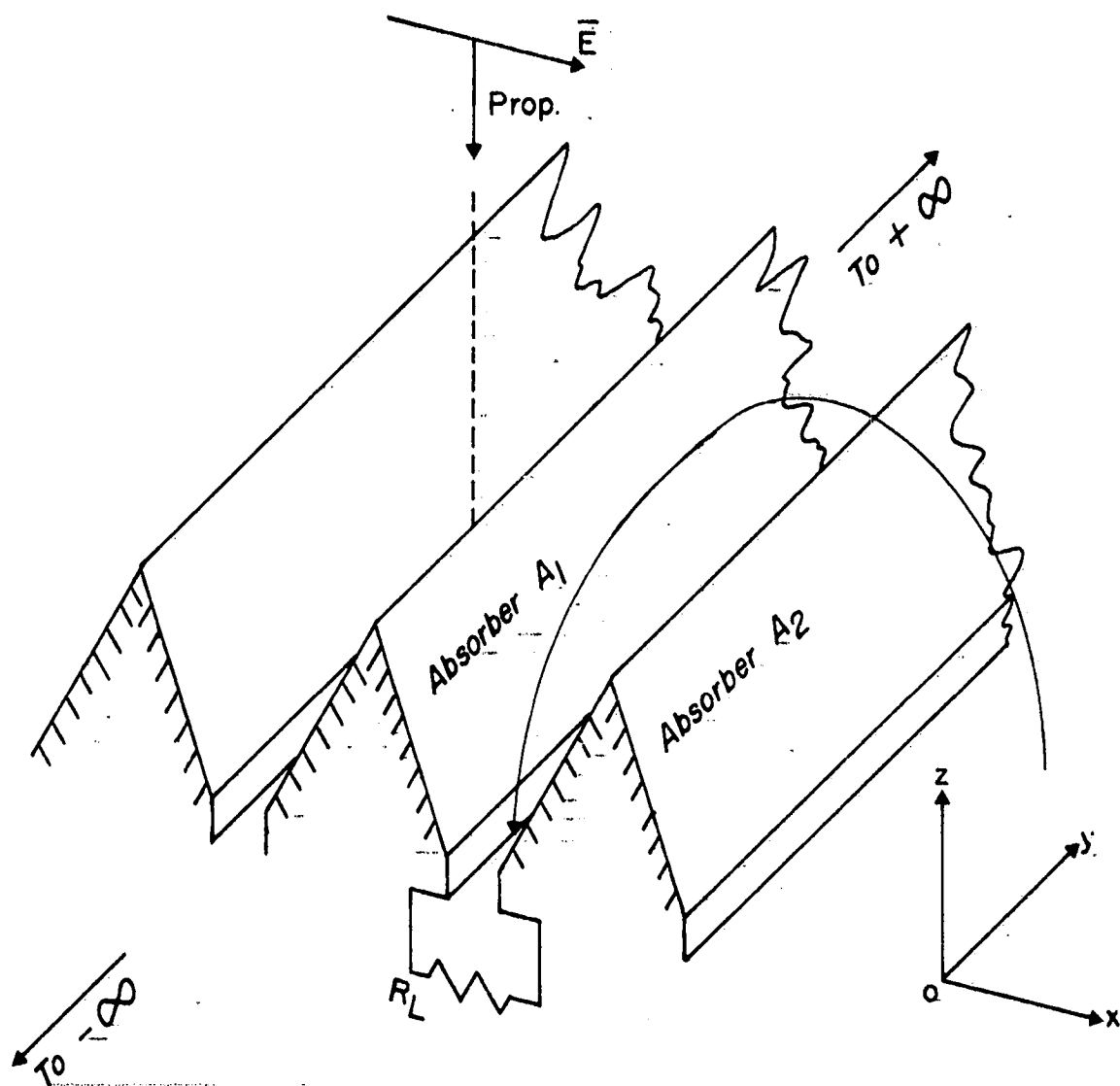


FIG. 6-1 Isometric View of EWEC-Type  
Surface Absorbers - 2 D Case

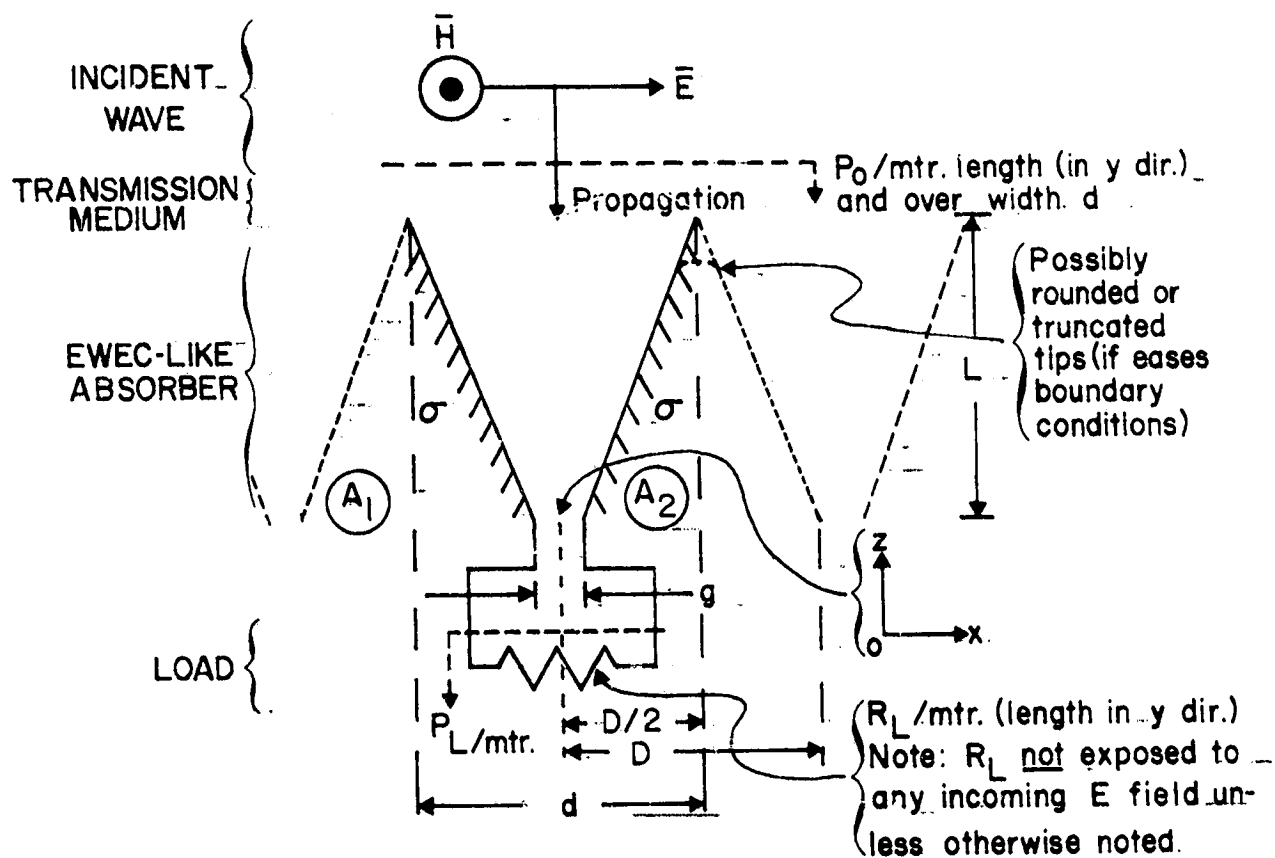


FIG. 6-2 End View Of Model For EWEC-Type Surface Absorbers - 2 D Case

$$P(\lambda) = P_0 \delta(\lambda - \lambda_0)$$

- Δ Propagation in -z direction and  $\perp$  to absorber plane.
- Δ  $\vec{E}$  = Electric field strength.
- Δ  $\vec{H}$  = Magnetic field intensity
- Δ  $\lambda_0$  = Its wavelength in free space

● Transmission Medium -- Free space characterized by:

- Δ  $\mu_0$  = Permeability
- Δ  $\epsilon_0$  = Dielectric constant
- Δ Homogeneous
- Δ Isotropic
- Δ Linear medium

● Absorber

- Δ Geometry: EWEC-like in 2 D as shown
- Δ Material: Arbitrary metal
- Δ Surfaces: Smooth surfaces on  $A_1$  and  $A_2$
- Δ Heights: All absorbers have same L.
- Δ Temperature: In thermal equilibrium

Models To Be Studied were defined as:

Model No.	Absorber Metal	Dimensional Range To Investigate.
1	Perfect Metal*	$\left\{ \begin{array}{l} 0 < L/\lambda_0 < 20 \\ 0 < D/\lambda_0 < 10 \\ g \text{ infinitesimal} \end{array} \right.$
2	$\sigma = \sigma_a$ , i.e. lossy metal	
3	$\sigma = \sigma_a + j\sigma_a$	
4	Model (1)	$0 < g/\lambda_0 < 10$
5	Model (2)	Ditto.
6	Model (5)	Ditto, except now $R_L$ becomes metal with $\sigma$ with $\vec{E}$ field irradiating its smooth metal surface.

\* Pure, lossless, homogeneous, isotropic

Analytical Goals For each model find:

1. Spatial distribution of surface currents on elements  $A_1$  and  $A_2$ . Include 'skin effect.'
2.  $I_L$ /meter of absorber length in y direction.
3. Spatial distribution of  $\vec{E}$  and  $\vec{H}$  fields between and in vicinity of  $A_1$  and  $A_2$ .
4. The conversion efficiency = absorptivity =  $\eta = \bar{P}_1/P_o$ . Account for all power, including any reflected out of the absorbers.
5. Whether there is an optimum  $L/D$  ratio (or  $L/\lambda_o/D/\lambda_o$ ), or optimum  $g$  (or  $g/\lambda_o$ ), or optimum  $\sigma$  (hence metal material) -- all using  $\eta$  as the principal optimization parameter.
6. For models No. 2 and No. 3, investigate  $A_1$  and  $A_2$  attenuation losses/meter length in z direction as a function of  $L$ .
7. For model No. 6 show that in the limit as  $L \rightarrow 0$  we have the classical case of an EM field irradiating a lossy surface.
8. Study phase relations of  $I_L$  in each  $R_L$  in adjacent troughs.
9. Briefly investigate -- if possible -- what effects cross slicing has, i.e. also slicing the metal surface in x direction, leaving tetrahedra.
10. What geometrical parameters principally affect the center receiving wavelength and the bandwidth of the absorber? This investigation should also examine whether such absorbing structures are receptive at other eigenvalue wavelengths and if so quantify the resulting  $P_L(\lambda)$  spectral distribution, particularly investigating whether the surface absorbs well at short  $\lambda$  but is a poor reradiator at longer  $\lambda$ , i.e. whether this type surface inherently has useful 'greenhousing effect.'

#### Justification Of Models

Here we lay out our rationale for the choices and ranges for the above models.

- Incident Wave The linearly polarized, coherent, monochromatic, uniform, plane wave arriving from one direction is the classic case in time varying EM field problems. It is known to give deep insights, quickly revealing what is and

isn't important. It is also known to be the simplest starting point. Finally, it corresponds exactly to the case of a laser beam impinging on an EWEC absorber, a problem of substantial theoretical and practical importance to NASA and other agencies.

We are well aware of the fact that the above incident wave does not accurately model the sun's radiation which is thought to be randomly polarized, phase-incoherent, stochastic in nature, and a power spectral density considerably different from a delta function. Such analytical modeling of the sun's radiation from the fields and waves viewpoint is a fundamental theoretical problem of both scientific and engineering importance. Mr. James Heaney, one of our graduate students, has chosen to investigate this research area for his Master's thesis.

- Transmission Medium - That chosen is for free space, the classic case. Effects of air, contaminants, density variations, attenuation of the sun's radiation through the atmosphere, and other effects are secondary for this first order modeling.

- Absorber

- Δ Model Nos. 1-3 progress from the ideal toward realistic metals at IR and light wavelengths where  $\sigma$  is known-to-be complex.
- Δ Metal is believed the easiest case to analyze, drawing on known tools in microwaves, horns, antennas, transmission lines, and related apparatus.
- Δ Smooth Surface metals on  $A_1$  and  $A_2$  are realistic for tetrahedra [30] and more-or-less conic [31] type metal surfaces known to have been fabricated to date.
- Δ Geometry That proposed is about the simplest envisioned which could give us a reasonable starting point for the analysis. We have earlier cited why the 2 D case was chosen for it. Also the geometry chosen appears about the simplest manufacturable EWEC geometry should its technical feasibility be indicated from the later analysis.
- Δ Length L was chosen to span the electrically short

to the electrically long-range. ( $0 < l/\lambda_0 < 20$ ) Insect antennae (which are dielectric, however) fall in this range. - Also Cuno's [31] solar thermal absorber -- which is metal and known to work with 96-percent absorptivity -- falls in this range. Finally, tapered waveguides, transmission lines, dielectric rod antennas, and other microwave devices where a transition is made from one medium to another fall in this approximate range.

The problem of statistically varying absorber lengths is recognized as a valid theoretical problem which could be dealt with later.

Δ Absorber Base Dimensions ( $0 < D/\lambda_0 < 10$ )

In human eye retinal cones  $D/\lambda_0$  is approximately 4. Also Callahan's data on insect sensilla show they all easily fall within this range.

Δ Absorber Spacing ( $0 < g/\lambda_0 < 10$ )

Model Nos. 1-3 are the simplest cases with  $g \sim 0$ , understanding the electrical load terminals are not shorted. This is the close spaced case. One finds close spaced arrays on insect antennae.

Model Nos. 4 and 5 would permit investigating the effects of deploying the absorbers in periodic array-like fashion by increasing  $g$ . These two models would also assume a 'perfect ground plane' between  $A_1$  and  $A_2$  penetrated by fictitious connecting wires to  $R_L$  (which is not irradiated).

Model 6 replaces the perfect ground with a ground plane having a conductivity the same as absorbers  $A_1$  and  $A_2$ . Thus the bulk resistance of the metal now becomes the 'load' in which the incident wave's power dissipates -- both by virtue of currents induced in  $A_1$  and  $A_2$  causing Joule heating in the metals and also by currents directly induced by the incident wave in the metal ( $J = \sigma E$ ) of the 'lossy ground plane.' This model, in particular, should give us considerable new insight into the nature of absorption of radiant wave energy by a metal surface with periodic roughness. It would be extremely significant to solar thermal absorption understanding and, in all probability, would lead to new 'selective surface' absorbers based on wave techniques.



This, then, completes the formal definition of the EWEC metals problem. The model has been explicitly defined and with care, considering inputs from Nature and known surface absorption phenomena. We believe the later analytical solution of the metals problem will be of substantial theoretical interest throughout the scientific and engineering communities and will, in all likelihood, later lead to practical designable surfaces where electromagnetic wave absorption is desired.

## Chapter 7

### THEORETICAL EWEC MODEL -- DIELECTRIC ABSORBERS

In this Chap. we present the proposed theoretical model for the EWEC dielectric case. The justification for dielectrics is in the first part of Chap. 6 as is the modeling rationale. The strong similarity of the dielectric model to that found on insect spines as elucidated in Chap. 5 will be evident, for indeed the proposed theoretical model is a first attempt at modeling Fig. 5-3 in a tractible form.

The presentation structure follows that of the Chap. 6 'metals' case.

Problem Formulation: EWEC Absorber - Dielectric Case

The Proposed Model is shown in Figs. 7-1 and 2. The incident wave, with field in the x direction, propagates in the negative z direction into dielectric EWEC absorbers  $A_1$  and  $A_2$  extending to  $\pm\infty$ . A load resistor of  $R_L$  ohms/meter (in y dir.) terminates each absorber as shown. In contrast to the earlier metal case, a coupling probe to extract the electrical energy is necessary with the dielectric case.

Assumptions To Be Made are:

- Incident Wave Same as for metals case.
- Transmission Medium Same as for metals case.
- Absorber
  - Δ Geometry: EWEC-like in 2 D as shown.
  - Δ Material: Dielectric with dielectric constant and permeability shown.
  - Δ Surfaces: Smooth surfaces inside and outside of dielectric absorbing elements. (No corrugations, no-slots, no holes, no log spirals, etc. as found on some

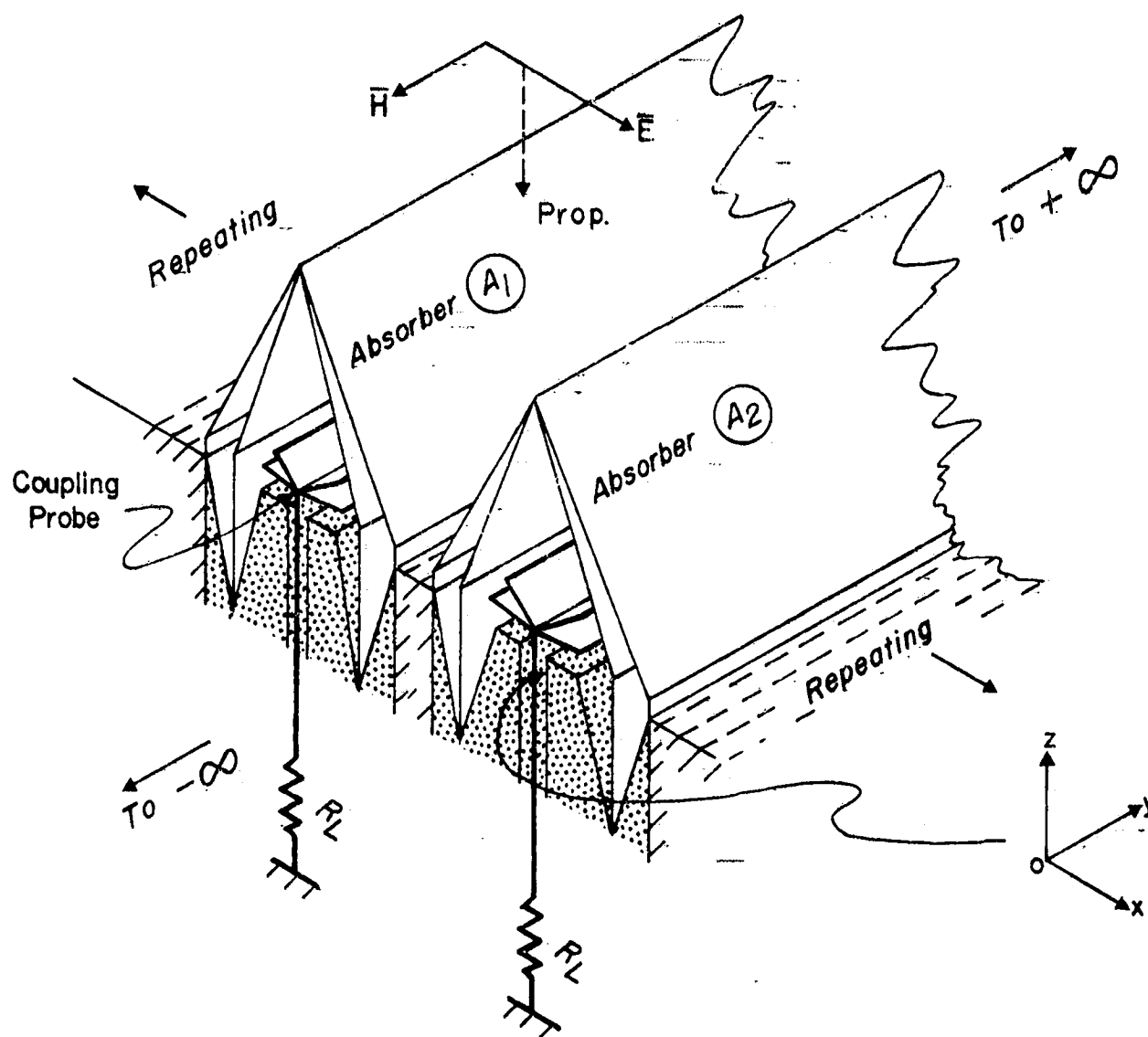


FIG. 7-1 Isometric View of EWEC-type Surface Absorbers - 2 D Dielectric Material Case..

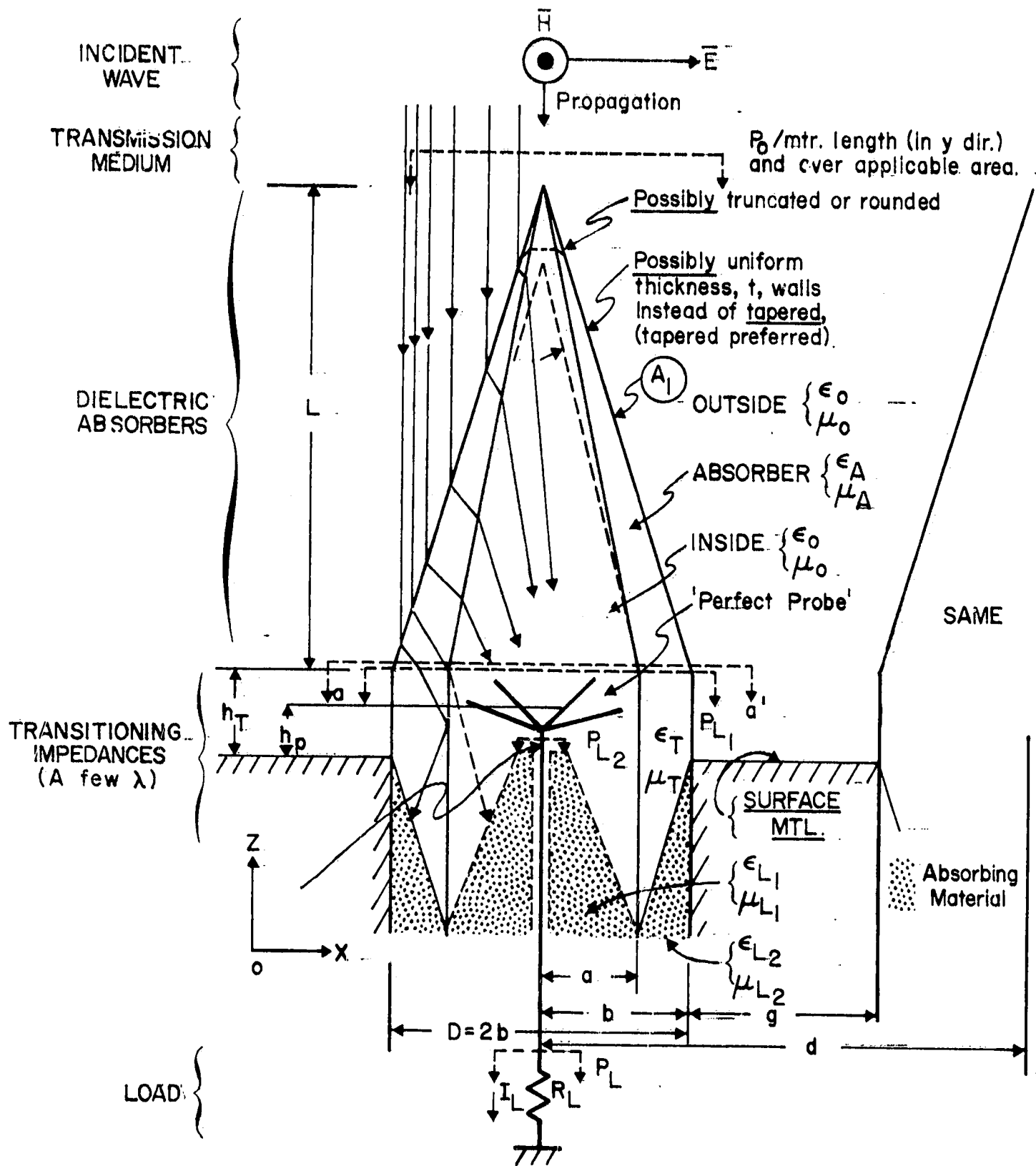


FIG. 7-2 End View of Proposed Model for Dielectric EWEC-type Surface Absorber — 2 D Case.

- insect antennae).
- Δ Heights: All absorbers have same  $L$ .
- Δ Temperature: In thermal equilibrium

### ● Transitioning Impedances

- Δ Upper Tube: Is an impedance matching section between — dielectric absorber above and the tapered— absorbing load below it.
- Δ Outer Cone: The taper, over a few  $\lambda$ , transitions— downward propagating wave into a dissi-  
pative load,  $\epsilon_{L2}\mu_{L2}$ . It's intrinsic  
impedance is chosen to completely  
absorb any downward propagating wave  
in  $\epsilon_T\mu_T$ .
- Δ Inner Cone: Its  $\epsilon_{L1}\mu_{L1}$ , chosen such that waves  
passing the probe are completely  
absorbed. The taper over a few  $\lambda$   
aids the gradual transition and  
absorption.

### ● Coupling Probe

- Δ Function: Is a 'perfect probe,' i.e. it captures  
all EM waves focussed on it.
- Δ Geometry: No variation in  $y$  direction. Since we  
are assuming it is 'perfect,' its detailed  
geometry is not presently important.
- Δ Output: An electrical current. The probe's  
output is via an assumed lossless  
transmission line to  $R_L$ .

### ● Load

- Δ Lumped: Equivalent of  $R_L$ /meter (in  $y$  dir.) and  
purely resistive.

Models To Be Studied were defined as:

Model No.	Absorber Material	Surface Material	Dimensional Range To Investigate
7	Lossless diel.	Doesn't matter (g infinitesimal) Perfect Metal* $\sigma = \sigma_a$ (lossy) <sup>+</sup> $\sigma = \sigma_a + j b_a$ Perfect Metal* $\sigma = \sigma_a$ (lossy) <sup>+</sup> $\sigma = \sigma_a + j b_a$	$0 < L/\lambda_o < 20$ $0 < D/\lambda_o < 6$ $0 < a/b < 1.0$ $0 < h_T/\lambda_o < 6$  $0 < g/\lambda_o < 10$
8	lossy diel.		
9	Model 7		
10	↓		
11	↓		
12	Model 8		
13	↓		
14	↓		

\* Pure, lossless, homogeneous, isotropic.

<sup>+</sup> Especially sub-cases of: (1) Realistic metals and (2) case where surface is intrinsically matched (377 ohms/square).

Analytical Goals For each model find:

1. Spatial distribution of  $\vec{E}$  and  $\vec{H}$  fields in and around absorber elements and in vicinity of probe. Limit study to dominant or most likely mode propagating with least attenuation losses/meter (in z dir.). Thought to be  $HE_{11}$  mode.
2.  $I_L$ /meter (in z dir.)
3. The conversion efficiency = absorptivity =  $\eta = P_L/P_o$ . Account for all power, including any reflected out of the absorbers.
4. Whether there are optimum ranges for:

$L/\lambda_o$  } → Determines optimum absorber geometry  
 $D/\lambda_o$  } → for max. absorptivity and conversion.  
 $a/b$  } → Determines wall thickness and losses.  
 $h_T/\lambda_o$  → Determine whether it is really needed and if so what size range is best.  
 $\epsilon$  and  $\mu$  → For all dielectric materials.

$\sigma \rightarrow$  Determines most desirable surface material.

5. For Model Nos. 8, 12, 13, 14, investigate attenuation losses/meter length in z direction as a function of L (or  $L/\lambda_0$ ).
6. For Model 7 show that when  $L/\lambda_0 \rightarrow 0$ ,  $D/\lambda_0 \rightarrow \infty$ ,  $h_T/\lambda_0$  finite,  $a/b \rightarrow 0$ ,  $h_P/\lambda_0 \rightarrow -\infty$  then the analytical results reduce to classical case of a wave impinging on a lossless dielectric.
7. For Model 8 show that when  $L/\lambda_0 \rightarrow \infty$  and when  $a/b \rightarrow 1.0$  and  $\epsilon_A = \epsilon_T$  and  $\mu_A = \mu_T$  then the analytical results approaches the cylindrical tube case analyzed by Kiely [46, Chap. IV].
8. For Model 7, under appropriate conditions to be found or inferred, show that when  $a/b \rightarrow 0$ , the absorber approaches the dielectric rod case analyzed by Kiely [46, Ch. III] et al. May have to assume  $h_T$  is large and that  $\epsilon_A = \epsilon_T$  and  $\mu_A = \mu_T$  to show it.
9. For Model 8, show that when the dielectric material is very lossy, the composite EWEC surface approaches a perfect absorber insofar as the incoming wave is concerned.<sup>1</sup> May have to choose material such that  $\eta_A = \sqrt{\frac{\mu_A}{\epsilon_A}} = 377$  ohms/square.
10. Study phase relations of  $I_L$  in each  $R_L$  under each absorber. Are they all in phase regardless of what  $g$  is?
11. What geometrical parameters principally affect the center receiving wavelength and bandwidth along the lines suggested for the earlier metals case.

#### Justification of Models

Here we lay out our rationale for the choices and ranges for the above models.

- Incident Wave Same considerations as for the metal case.
- Transmission Medium Ditto.

<sup>1</sup> It will be a poor converter to electric power in  $R_L$  under these conditions, however. This case corresponds roughly to the anechoic surfaces manufactured by Emerson & Cummings [81] and analyzed by Cherepanov [28].

## ● Absorber

- Δ Models Progress from simplest lossless case (Model 7) to the most complex (Model 14) with lossy dielectric spines and a surface metal with complex conductivity with adjacent absorbers similarly arrayed.
- Δ Dielectrics Callahan's 1967 insect work [21] clearly shows insect spines are dielectric with dielectric constant in the 2.5-3.0 range and that such a dielectric constant about matches that of various waxes found on insect sensillae surfaces and that Kiely's experimental work [46] on dielectric antennas was based on similar dielectrics. His later extensive research cited in Chap. 5 and 6 collectively supports the dielectric idea.
- Δ Smooth Surfaces appear to be the only sensible tractable case to choose at this time.
- Δ Geometry Essentially that suggested from the insect sensillae, Chap. 5. We cited in Chap. 6 why the 2-D case was chosen.
- Δ Length L Same considerations as for the metals case.
- Δ Base Dimension ( $0 < D/\lambda_0 < 6$ ). Same considerations as for the metals case.
- Δ Hollow vs Solid Precisely what material is inside the insect's spine is not known. Air was chosen as the simplest starting point. If it is later found another dielectric constant material is inside instead, it is believed the analysis of the simpler air case chosen could be relatively easily modified.
- Δ Rounding/Truncation/Curving of the spine ends are found on insects, but the straight sharp pointed one chosen is the most common on insects. Also Kiely [46, p 29] indicates that McKinney had earlier found curving a solid dielectric waveguide near the end markedly increases the attenuation for small radius of curvature.

An extreme-example of rounding occurs in the corneal nipples of insect eyes. The chosen theoretical model, Fig. 7-2, covers this case too,



If we let  $a \rightarrow 0$  and  $L = \text{nipple radius} = b$ .

Δ Absorber Spacing ( $0 < g/\lambda_0 < 10$ ).

Models 7 and 8 are simplest case where  $g = 0$ .  
This corresponds to the close-packed idea common  
in Nature's wave absorbers.

Models 9-14 would permit systematic investigation of deploying the absorbers in array-like fashion as found on insects by increasing  $g$ . They also cover the ground plane cases from perfect to lossy. These models are set up so as to cover all the theoretical cases likely to be of any later design importance.

- The Probe The need for a probe of some kind to couple the EM energy out is obvious in light of Chap. 5 geometry found on insects. It is assumed 'perfect,' a part of which implies it is lossless. Its details are not essential to know at this point to make analytical progress.
- Transitioning Impedances The rationale for these choices was essentially covered under 'Assumptions' above, except for the fact that there are fewer transitioning sections chosen for the Fig. 7-2 model than exists on insect spines, Fig. 5-3. This choice was made in the hopes of simplifying the analysis; but it should not be forgotten that Nature's structures have more transitioning sections than we have chosen for this first model.

This completes the formal definition of the EWEC dielectrics problem. The model has been defined with care and along the general lines as was the EWEC metal problem of Chap. 6. It is clear, however, that the dielectric problem is substantially more technically complex than the metals problem. We believe the later analytical solution of the dielectric problem -- in addition to advancing EWEC research, especially solar=electric conversion possibilities via such EWEC structures -- will also have substantial spin-offs to entomologists and others interested in insect control.

## Chapter 8

### EFFICIENCY COMPARISON -- METAL VS DIELECTRIC ABSORBERS

Rationale -- Chapters 6 and 7 explicitly defined -- but not solved -- the two principal theoretical models of most relevance to EWEC absorber research, (1) the metal case and (2) the dielectric case. If the  $\vec{E}$  and  $\vec{H}$  field expressions for these two major cases were known for all space in and near the models, then application of classical field methods would show the theoretical losses for each, permitting a clear choice of best material type to be made. All future EWEC research would then rest on that choice. Thus the lowest loss material would result in the highest conversion efficiency solar-electric absorber. Put the analytical difficulties in obtaining such solutions, while we believe not insurmountable, are indeed formidable, and such results are not presently available.

In this Chap. we briefly inquire into an alternate approach aimed at roughly estimating the losses -- hence, conversion efficiency  $\eta$  -- for the two cases, fully recognizing the need for later verification and refinement of these early estimates. Our approach here is based on very rough models which do not exactly fit those set up in Chaps. 6 and 7. Nevertheless they can give us some loose guides for making early rough estimates of probable  $\eta$  for absorbers to be used on EWEC solar-electric converters.

The desirability of achieving high  $\eta$  is well recognized in any solar-electric direct radiant converter and need not be argued.

### Loss Comparisons In Various Guiding Structures

DiDomenico, a Bell Laboratories fiber optics engineer, in a most significant paper [33], succinctly compares losses in several types of electrical wave guiding structures of practical importance. He showed that: —

- Twisted Pair Wires have a 5 db/Km loss at 10 KHz.
- A Coaxial Line of 0.375 in. diameter has a loss of 5 db/Km at about 10 MHz.
- A Millimeter Waveguide of 2 in. dia. has a loss of about 1 db/Km at about 100 GHz.
- An Optical Fiber, of best present art material, has a loss of only about 2 db/Km in the solar spectral range.<sup>1</sup>

He argues, as Ramon and Whinnery have long ago shown [61], that the first three of these have frequency dependent losses (they generally increase with frequency -- i.e. shorter wavelength -- for operation well above the cut-off frequency). Such guided structures require equalization whereas the loss in a fiber optic medium is low and is independent of the baseband frequency. He also states that gigahertz bandwidths are possible with singlemode fiber optics.

Losses In Fiber Optics Di Domenico summarizes the dramatic progress recently made in reducing losses in optical fibers, from 20 db/Km achieved in 1970 by Corning Glass Works to 2 db/Km achieved in the summer of 1974 by Bell Labs using a fused-silica-core fiber. The fiber

<sup>1</sup> Communications engineers creating new fiber optic communication systems naturally are interested in kilometer lengths. Such light pipes are billions of light wavelengths long. In considering such materials for possible use in EWEC solar-electric absorbers, note that our interest is only in rods  $\sim 10 \lambda$  long.

materials which appear most attractive are high silica or borosilica glasses. These glasses can be doped to control the refractive index. We reproduce in Fig. 8-1 Di Domenico's principal-loss curve. "The graph shows the wavelength - dependence of the loss measured on a 1200 meter section of multimode fiber made by the Corning Glass Works and a 723 meter section of a multimode fiber made by Bell Labs. Note that the loss reaches values of 4 and 2 db/Km at 0.85  $\mu$ m and 1.06  $\mu$ m respectively. The low loss window between 0.8 and 0.85  $\mu$ m matches the output wavelength from GaAs lasers doped with Al. The large absorption band centered at 0.95  $\mu$ m is due to the presence of OH ions in the glass."

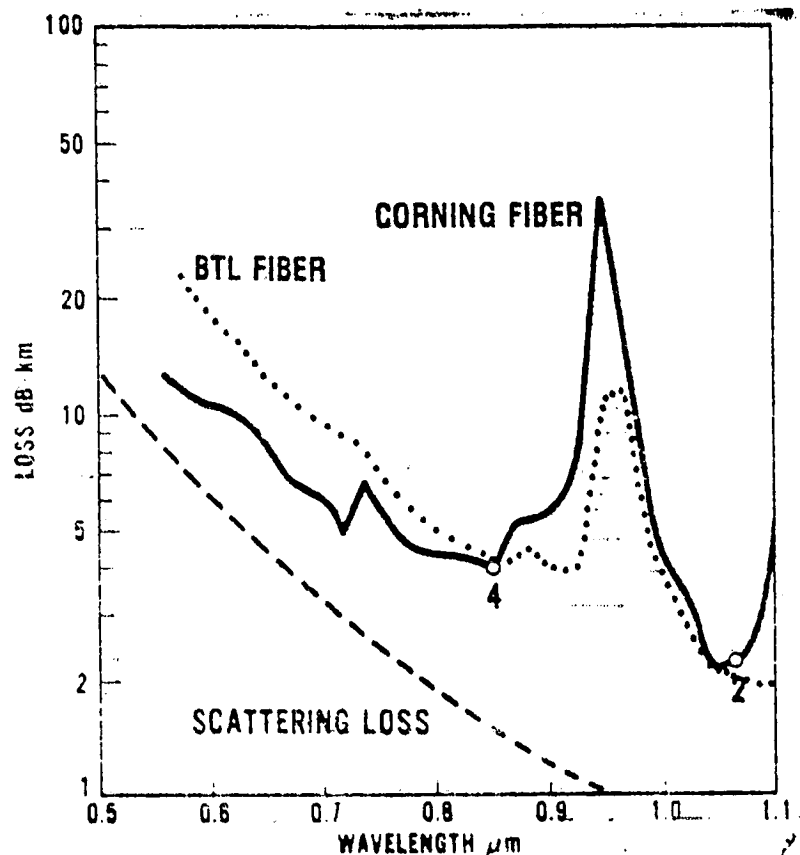


FIG. 8-1 Di Domenico's [33] Measured Loss Curve for State-of-the-Art Fiber Optics.

We believe Di Domenico's results on loss measurements in fiber optic glasses potentially significant for EWEC Solar-electric Converters because: - -

- The dielectric materials are probably close to the best known in the present dynamic fiber optics technology, though we have not carefully researched this field in this short grant.
- The fiber optic materials are of glass which is known to be one of the most durable materials when subjected to solar radiation, as such fibers would be if assembled into EWEC solar-electric converters. Glasses would seem to be of particular interest as EWEC dielectric absorbers, especially in view of Callahan's SEM micrographs of insect sensilla, most of which show the spines made of a transparent material.
- Di Domenico's data are based on actual measurements and not calculations. -
- His data are approximately in the wavelength range of most interest for any EWEC solar-electric converter, i.e.,  $\sim 0.3\mu\text{m} - 1.1\mu\text{m}$ .
- The data are based on small (about  $100\mu\text{m}$  O. D.) circular cross-section dielectric rods. Circular geometry dielectric rods roughly in this size range -- or preferably smaller -- are most relevant to EWEC solar-electric absorbers. The losses in thin walled tubes probably needed for the best EWEC absorbers would be even less than those for a solid rod.

We found it interesting to take Di Domenico's lowest loss case, at about  $1\mu\text{m}$ , translate this to a section only  $10\lambda$  long (to correspond with about the longest spine one finds on insects), and then calculate the conversion efficiency of such an EWEC 'antenna,' considering the  $10\lambda$  rod as one element. The results showed a loss of  $2.2 \times 10^{-8}$  db for the  $10\lambda$  section which corresponds to an EWEC absorber efficiency of  $\eta = 0.99999995$ . This estimated absorber

efficiency would be 'optimistic.' We then repeated the calculation at 0.95 $\mu$ m where the loss is highest, resulting in a calculated 'pessimistic' absorber efficiency of 0.9999999194.

Losses At Microwave-Frequencies For Dielectric Antennas Kiely [46, p 79] shows that for a dielectric rod waveguide (polystyrene with dielectric constant = 2.5) of 0.46  $\lambda$  diameter, operating in the  $HE_{11}$  mode at microwave frequency<sup>1</sup> the attenuation is about 0.1 db/wavelength. The same 10  $\lambda$  spine estimate of the previous paragraph would thus translate to a 1.0 db loss or an absorber efficiency of about 79 percent. Kiely concludes that "even for dielectric rod aeriels several wavelengths long the attenuation is small provided the loss tangent of the dielectric is of the order of  $10^{-3}$ ".

Mueller [57], reporting on the WW II work done on dielectric antennas at Bell Labs, also briefly investigated their losses at microwave frequencies. Measurements were made near 3000 MHz on 6  $\lambda$  tapered dielectric antenna rods of rectangular cross section ( $1/4\lambda \times 1/2\lambda$ ) for several different materials having power factors of: styramic 0.0005, Hard rubber .003, and acetate butyrate 0.020. The relative responses are reproduced in Fig. 8-2. Thus at microwave frequencies Mueller's data clearly show that high loss dielectric materials result in less relative output from a polyrod antenna, as would be expected. The width of the beam at half power points appears negligibly affected by

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<sup>1</sup>Unfortunately, Kiely's explanation is less than clear on what wavelength. He seems to imply wavelengths in the 10 CM. range.

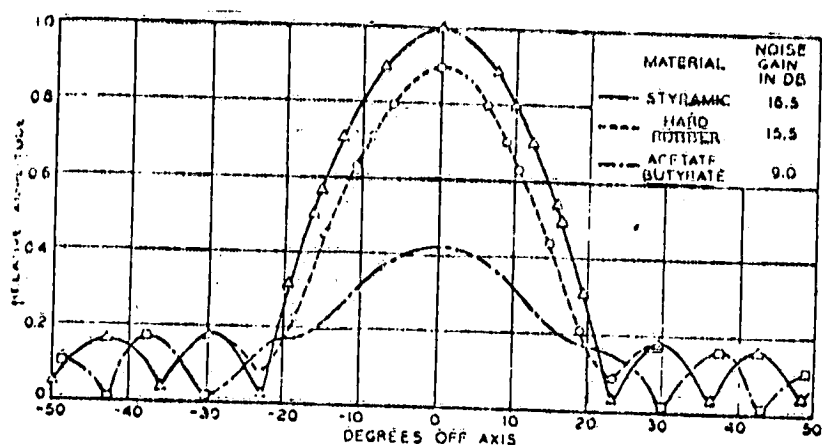


FIG. 8-2 Measured Effect of Dielectric Loss on Polyrod Performance. Mueller [57]

absorber losses for these measurements. Mueller concludes that materials having power factors less than 0.001 are satisfactory for polyrod antennas-- exactly the same figure Kiely found.

The validity of extrapolating these microwave results to the optical range may be open to question, but Mueller's results suggest to us that, as one would expect, materials chosen for the dielectric spines in EWEC should be low loss materials (loss tangents less than 0.001) in the solar range and that one could expect the absorber conversion efficiency to fall off if lossy dielectrics were chosen.

The latter case then tends toward a solar-thermal converter where, in the limit, all the incident wave power would be dissipated in the lossy dielectric spines exactly as in microwave anechoic material. This case would also be similar to various rough surface organic coatings used on solar thermal absorbers, as such coatings are probably lossy dielectrics.

Loss Comparison: Dielectric Rods vs Coaxial Cables McKinney [51], in one of the early significant papers on dielectric waveguides and radiators, made measurements at microwave frequencies -- apparently at about 3.2 CM. wavelength -- of attenuation in rods made of lucite ( $\tan \delta = .01$ ) and textolite ( $\tan \delta = .001$ ) for various modes. He normalized his results, comparing the measured attenuation in the dielectric rods with that of a coaxial cable. He then compared these measured values with earlier theoretical predictions by Wagener who did some of the earliest work on dielectric antennas. We reproduce McKinney's results here in Figs. 8-3 and 8-4.

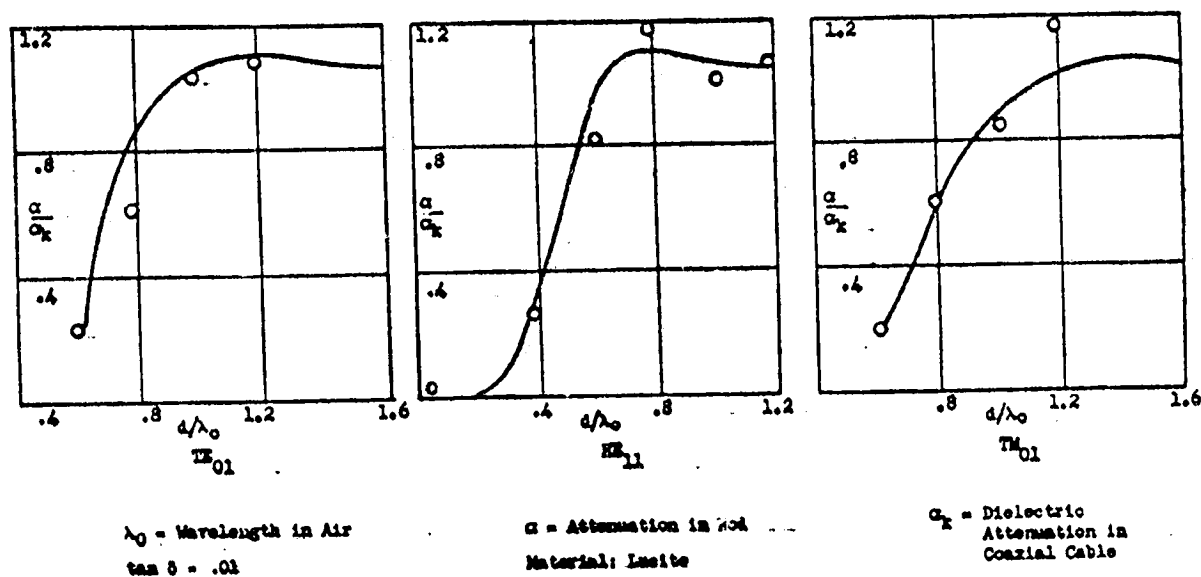


FIG. 8-3 The Dependence of Attenuation in a Dielectric Rod on the Diameter,  $d$ , of the Rod. Solid Curves are Theoretical Values [51].

McKinney's results suggest to us that, to a first approximation, the guide mode is not extremely critical, all the attenuation curves



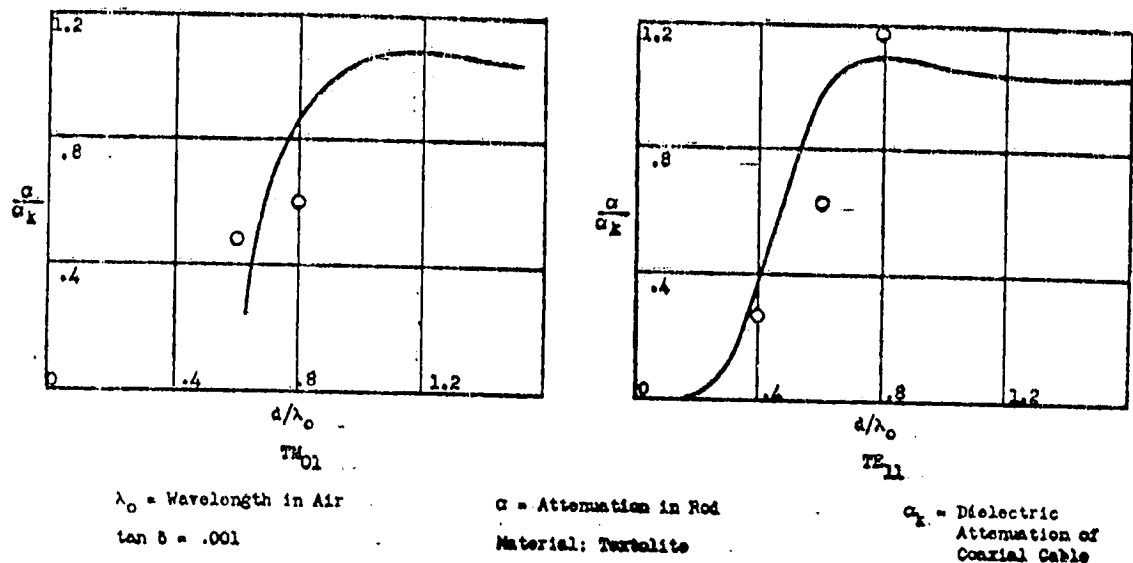


FIG. 8-4 The Dependence of Attenuation,  $\alpha$ , in a Dielectric Rod on the Diameter,  $d$ , of the Rod Solid Curves are Theoretical Values [51].

falling in the same approximate range.

More important is the matter of the diameter of the dielectric rod. His curves suggest, when applied to EWEC absorber elements, that it is desirable to structure the absorber rods so that their  $d/\lambda_0 < \text{about } 0.4$  if losses are to be minimized. Again, one can easily relate this finding back to Chap. 5 where one finds most insect spines structured long and slender.

McKinney's data in Figs. 8-3 and 8-4 further suggest that if the rod diameter is of the order of  $1 \lambda$  or larger, then the losses in the rod are large and may equal or exceed those one would have in a coaxial cable (metal) operating at that wavelength. It is not hard for us to see, after examining SEM photographs of the microstructure of known good

solar-thermal absorber surfaces used by NASA, -- Peake [69] --, that the organic paint coatings (lossy dielectrics) tend toward hills or mounds with diameters of the order of the wavelength of the incident radiation, which fact appears to nicely fit McKinney's curves.

Finally, Figures 8-3 and 8-4 imply the important result that dielectric guide structures for solar-electric converters can be more efficient than metallic guide structures (coax) if the diameter is properly chosen, in relation to the incident wavelength. For EWEC solar-electric absorbers his results suggest going toward small diameters to achieve higher conversion efficiency, a result again observable in Nature on the insect spines but not previously recognized by us as of importance in minimizing absorber losses -- or conversely -- maximizing converter efficiency.

In Summary, our knowledge at this early point in EWEC theoretical research in regard to whether metal or dielectric materials are best for EWEC converters is of a preliminary and most incomplete kind. Much more research needs to be done in this important area. Nevertheless, in spite of the many unknowns, the evidence accumulated to date suggest to us these very tenuous conclusions:

- Metals or highly lossy dielectrics -- perhaps on a metallic surface -- appear best for solar-thermal EWEC absorbers.
- Dielectrics of low loss materials appear best for solar-electric EWEC absorbers and that:
  - Δ Fiber optic glass should be a principal material candidate. Our very rough calculations indicate that in the solar range  $10 \lambda$  long absorbers could have an efficiency in the 99 plus percent range. If one considers that ordinary  $1/8''$

thick windowpane glass has a transmissivity of about 90% (many light wavelengths long), such estimated high absorber efficiencies for EWEC do not seem unreasonable. Other low loss dielectric materials should also be explored in far more depth than has been possible in this short grant.

- The spine diameter should be small in relation to the wavelength (about 0.4 or less), being received to minimize losses or maximize conversion efficiency.
- All the available loss data on dielectric antennas are for solid rods whereas insect sensillae suggest the spines be hollow and tapered, further suggesting the attenuation losses will be even less than estimated here for a solid rod.

As Chap. 9 indicates, it is also ideally necessary for the EWEC absorbers to be tuned to the mean incident wavelength and to have at least the same bandwidth as the incident spectrum.

Putting both the materials considerations of this Chap. and the bandwidth limitations of Chap. 9 together, it now appears that a conservative estimate of EWEC solar-electric absorber efficiency of about 90 percent could be achieved by suitable design and material choices; but a more rigorous analysis may modify this figure somewhat.

## Chapter 9

### BANDWIDTH -- A THEORETICAL LIMITATION ON EWEC ABSORBERS

#### 9-1 The General Problem Defined

Two important theoretical cases were seen:

- Case I Find the fundamental relationships between the irradiating power spectrum at the converter and the bandwidth of the EWEC converter for a single absorber element. In particular, the effect of the converter bandwidth on the converter efficiency is desired.
- Case II Since multiple length EWEC elements are also anticipated in practical converters,<sup>1</sup> a rough appraisal of the effects of these on maximum efficiency should be known along with whether this is the right direction to proceed.

Both cases are of theoretical importance for microwave, laser power conversion, and solar conversion (thermal and electric).

Only rough order-of-magnitude models and analysis estimates were felt needed at this early stage of the research. The analysis is similar to that used in modern electrical communications system theory.

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<sup>1</sup> Again, we take our cue from Nature via the morphology of insect antennae where multiple length absorbers each resonant at a different wavelength are a fact.

## 9-2 CASE-I ANALYSIS

### The Macroscopic Model

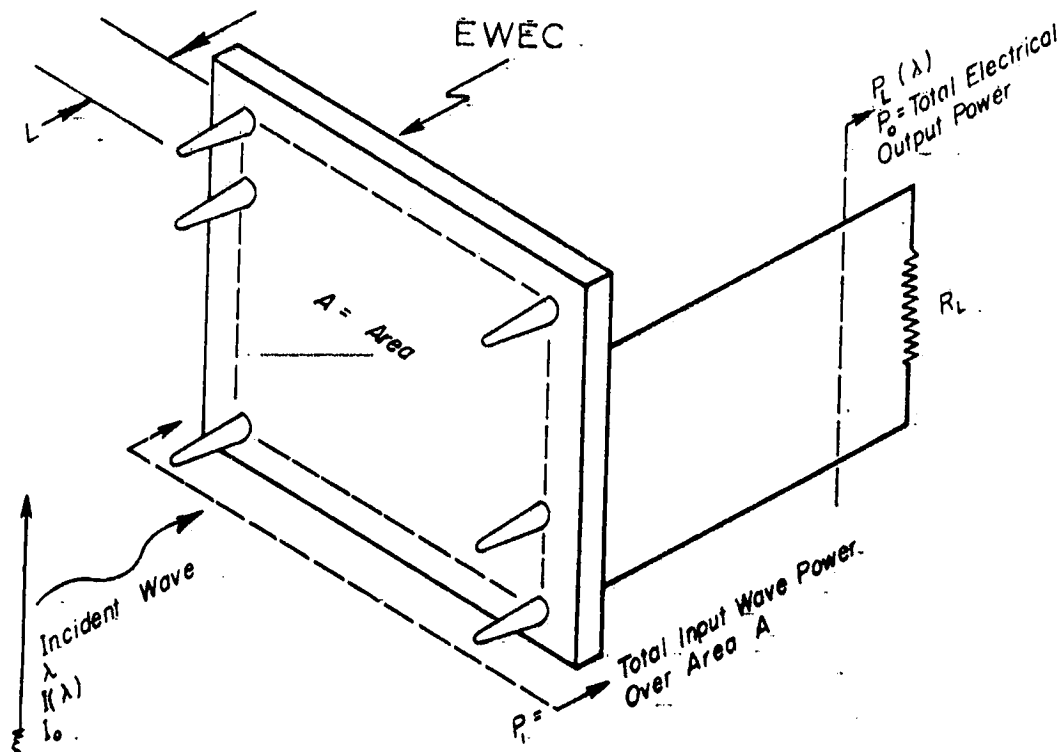


FIG. 9-1 First-order macroscopic model for Electromagnetic Wave Energy Converter with single length absorber elements.

#### Assumptions And Definitions

We assume:

1. Analysis Is Limited to a converter of the general EWEC type with principal interest in its power conversion aspects.
2. Internal Embodiment details and circuitry of the EWEC converter are not needed at this time for a first-order analysis. The converter is presently considered to be an array of absorber elements without rectifiers. We consider the converter in a macroscopic sense as an absorber of electromagnetic waves whose useful output power,  $P_o$ , appears in  $R_L$  — here considered a lumped element.

3. Converter Orientation is perpendicular to the direction of the incident propagating wave. The more complex case of other arrival angles is not considered in this early analysis.
4. The Incident Electromagnetic Wave has:
  - a. A single wavelength,  $\lambda$ , i.e. it is monochromatic.
  - b. Phase coherence, i.e. has a constant phase w.r.t. some reference, for any single  $\lambda$  value.
  - c. Plane Polarization, i.e. its electric field vector,  $\vec{E}$ , is oriented in a single direction at all times. This is the case for laser and microwave power transmission but is not the more complex case for the sun which is randomly polarized.
  - d. A Characteristic Power Spectral Density function,  $I(\lambda)$  watts/M<sup>2</sup>-micrometer.  $I(\lambda)$  is defined as the power in the impinging wave per square meter of absorber area for the wavelength interval between  $\lambda$  and  $\lambda + d\lambda$  micrometers. It is also technically known as the irradiance.  $I(\lambda)$  permits handling the more complex case beyond (a) where the incident wave is the summation of independent waves at several wavelengths.
  - e. An Intensity of  $I_0$  watts/M<sup>2</sup>  $= \int_0^{\infty} I(\lambda) d\lambda$
5. Focus is on the wave as it arrives at the EWEC converter, i.e. we are not concerned here with how it was launched, the antenna pattern of its transmitter and hence its spatial variation, its attenuation en route, and other unnecessary details.

6. Converter Efficiency is defined as:

$$\eta = P_0 / P_1$$

Note that this definition implies a given incident power spectral density via  $P_1$ .

7. Converter Power Gain is defined as:

$$G_c = \frac{P_L(\lambda)}{P_1(\lambda)}$$

where  $P_1(\lambda)$  = uniform 'white' irradiation power spectral density. Defining the converter power gain characteristic in this way results in a converter-gain characteristic determined solely by the converter. 'Converter power gain' and 'converter efficiency' are not necessarily equal.

8. Converter Bandwidth,  $B$ , is defined as the spectral range (Micrometers) over which the EWEC converter yields a useful  $P_o$  when irradiated with a wave of uniform ('white') power spectral density, i.e.  $P_1(\lambda) = \text{constant}$ . A more rigid definition, applicable to non-ideal converter gain characteristics, would be based on the half-power points with the bandwidth being the range (micrometers) between these.
9. The Impulse Function,  $\delta(\lambda - \lambda_1)$ , is defined in the usual way as having infinite height, centered on  $\lambda_1$ , and an area of 1.0 under its curve.
10. Superposition of waves and powers is assumed valid throughout.

#### ANALYSIS

Further Assumptions The absorber element length  $L$  is chosen so the converter's power response centers on the incident wavelength,  $\lambda_1$ , i.e. the absorber is tuned to the incident wavelength. The converter bandwidth,  $B$ , is finite and small compared to the center wavelength, i.e.  $B/\lambda_1 \ll 1$ . This case corresponds to an unmodulated microwave or laser power beam irradiating an EWEC power converter.

Is there a fundamental ceiling on the converter's efficiency for this case?

The relationships can easily be seen in Fig. 9-2.

The incident power  $P_1$  on the EWEC converter is

$$P_1 = AI_o = A \int_0^\infty I(\lambda) d\lambda = A \int_0^\infty A_o (\lambda - \lambda_1) d\lambda$$

$$P_1 = AA_o$$

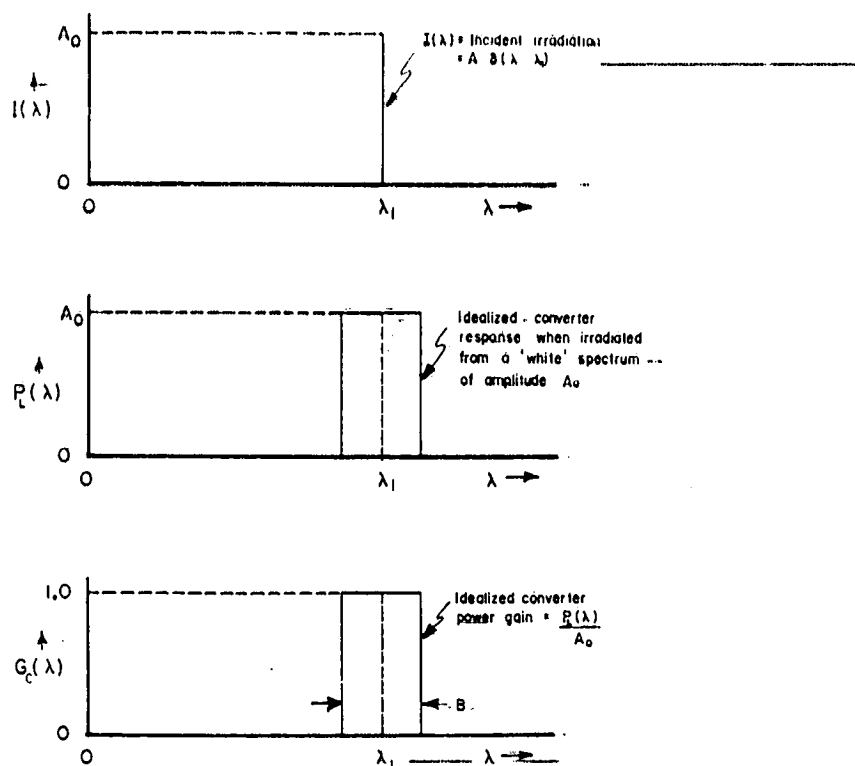


FIG. 9-2 Incident power spectral density  $I(\lambda)$ ,  $P_L(\lambda)$ , and idealized converter power gain  $G_c(\lambda)$  for the simplest case of all centered on  $\lambda_1$ .

The load power spectral density is, in general,

$$(1) \quad P_L(\lambda) = A G_c(\lambda) I(\lambda)$$

The maximum total power the load can have for the given irradiating  $I(\lambda)$ , assuming all the incident power is absorbed in the converter is:

$$P_o = \int_0^\infty P_L(\lambda) d\lambda = A \int_{\lambda_1 - B/2}^{\lambda_1 + B/2} A_0 \delta(\lambda - \lambda_1) d\lambda$$

$$P_o = AA_o$$

Thus the maximum converter efficiency when irradiated with the assumed  $I(\lambda)$  monochromatic wave is



$$(2) \quad \eta = \frac{P_o}{P_1} = \frac{\Lambda \Lambda_o}{\Lambda \Lambda_o} = 100\%$$

The maximum efficiency would be 100 percent as long as the converter passband 'covers'  $\lambda_1$ . If it does not, the efficiency would be zero.

We conclude for this simple case that there is no external limitation preventing EWEC converters from approaching 100% efficiency. The limitations are entirely within the converter and determined by the losses therein, as expected.

#### 9-2.1 SUB-CASE A

Now assume the incident radiation power density is widened to equal the converter bandwidth. This case fits that of a modulated power laser or microwave source irradiating an EWEC converter centered on  $\lambda_1$ . Is there a ceiling on the converter efficiency  $\eta$  for this case? The situation is shown in Fig. 9-3. The incident power is

$$P_1 = A I_o = A \int_0^\infty I(\lambda) d\lambda = A \int_{\lambda_1 - B/2}^{\lambda_1 + B/2} A_o d\lambda = \Lambda A_o B$$

The maximum total power is

$$P_o = A \int_0^\infty P_L(\lambda) d\lambda = A \int_0^\infty G_c(\lambda) I(\lambda) d\lambda = A \int_{\lambda_1 - B/2}^{\lambda_1 + B/2} A_o d\lambda$$

$$P_o = \Lambda A_o B$$

Thus the maximum converter efficiency when irradiated with the given  $I(\lambda)$  is, as expected,

$$(3) \quad \eta = \frac{P_o}{P_1} = \frac{\Lambda A_o B}{\Lambda A_o B} = 100\%$$

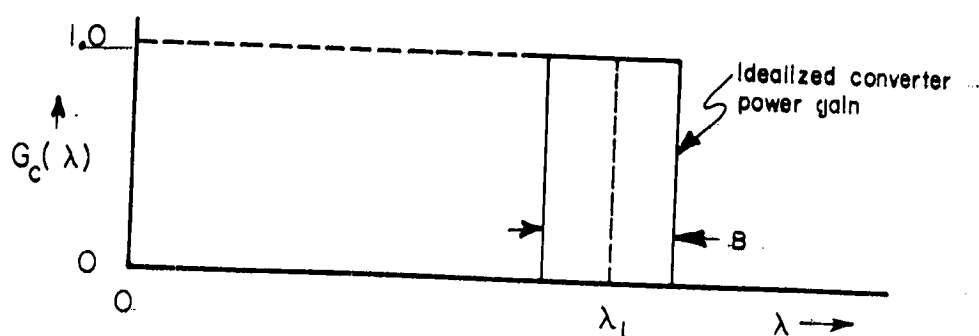
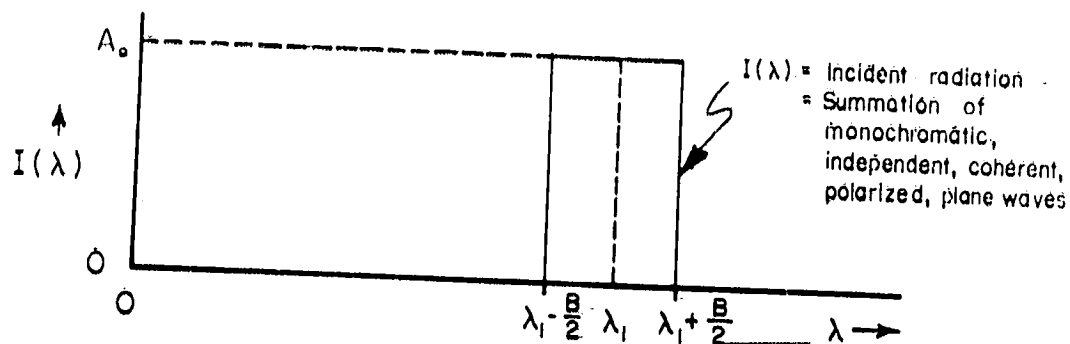


FIG. 9-3 Incident power spectral density and converter power gain when both have identical bandwidths  $B$  and are centered on  $\lambda_1$ .

Again there is no external limitation on achieving 100% converter efficiency.

#### 9-2.2 SUB-CASE B

Now assume the incident radiation power spectral density is further widened so that its bandwidth,  $B_i$ , always exceeds the converter bandwidth  $B$ .

Is there a ceiling on  $\eta$  for this case?

The situation is shown in Fig. 9-4.

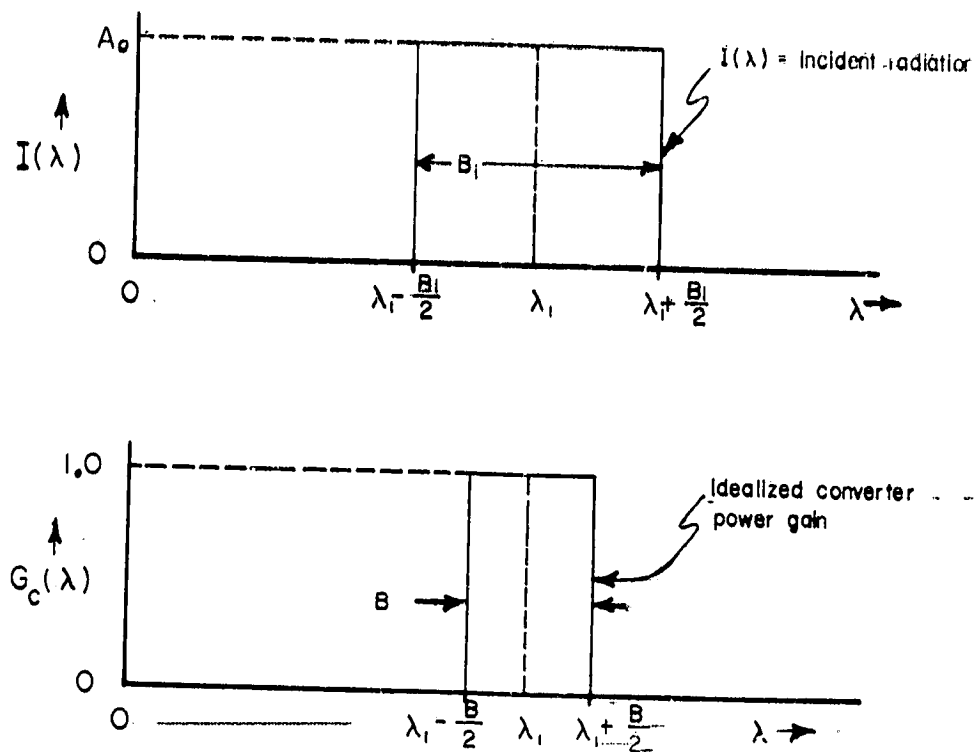


FIG. 9-4 Case where the converter bandwidth is narrower than the incident power spectral density.

The incident power is

$$P_1 = A I_0 = A \int_0^{\infty} I(\lambda) d\lambda = A \int_{\lambda_1 - B_1/2}^{\lambda_1 + B_1/2} A_0 d\lambda = A A_0 B_1$$

The maximum load power is

$$P_o = A \int_0^{\infty} P_L(\lambda) d\lambda = A \int_0^{\infty} G_c(\lambda) I(\lambda) d\lambda = A \int_{\lambda_1 - B/2}^{\lambda_1 + B/2} A_0 d\lambda$$

$$P_o = A A_0 B$$

And the maximum converter efficiency is

$$(4) \quad \eta = \frac{P_o}{P_i} = \frac{AA_o B}{AA_o B_i} = \frac{B}{B_i} \leq 100\%$$

The assumption is that the converter passband lies within the incident radiation passband. If it lies outside the incident passband the efficiency becomes zero. Obviously we would not want to design the converter for the latter case. If the converter passband lies partly within and partly outside the incident spectrum, i.e. it is improperly tuned, the converter efficiency will be correspondingly reduced. This trivial case is not treated here, as one would not intentionally design such a system.

The Conclusion for this sub-case is that for a fixed incident radiation bandwidth,  $B_i$ , the maximum converter efficiency is directly proportional to the converter bandwidth  $B$  until it equals the incident radiation bandwidth. Thereafter the efficiency stays constant at a maximum value of 1.0.

We summarize the results of the Case I analysis in Fig. 9-5.

The result has important implications for EWEC research in microwave, infrared, and solar spectral ranges. It clearly says that, ideally, the converter bandwidth must 'match' or exceed that of the incident radiation if conversion efficiencies approaching 100% are sought. There appears to be no particular theoretical advantage, however, in having the converter bandwidth appreciably exceed  $B_i$ . Finally the absorber must be tuned to the same principal wavelength as the irradiating electromagnetic wave -- a result not commonly appreciated.

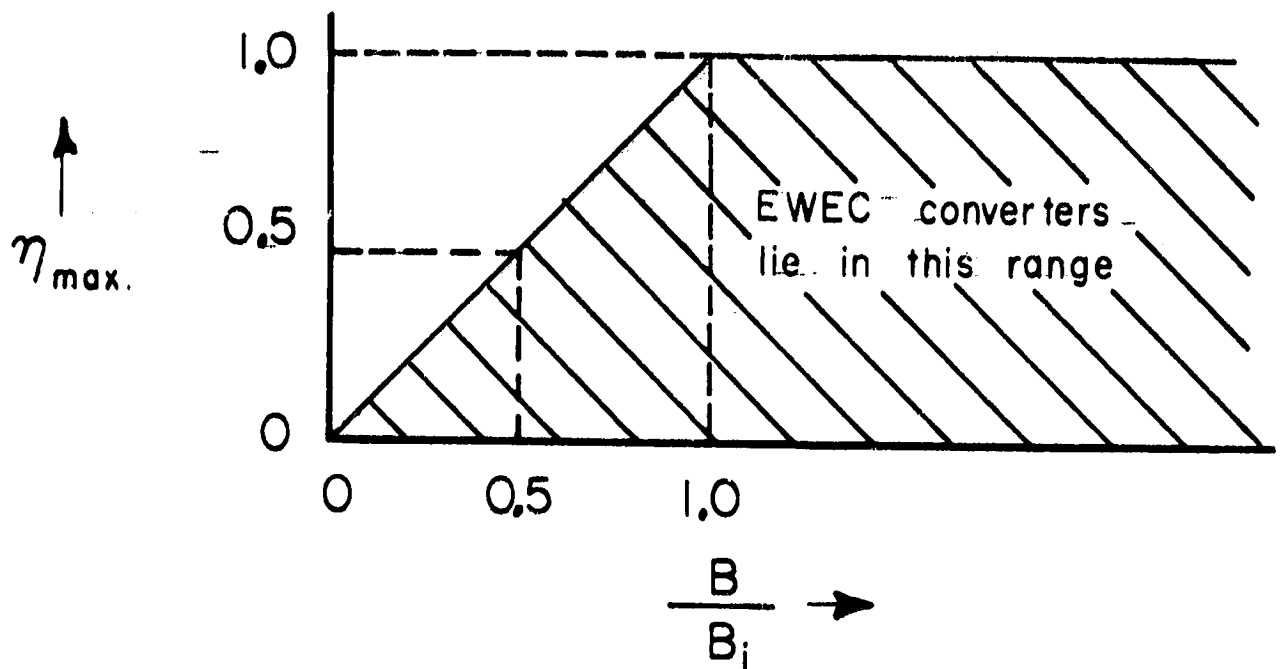


FIG. 9-5 Plot of maximum converter efficiency as a function of bandwidth ratio  
 $\frac{B}{B_i} = \frac{\text{Converter Bandwidth}}{\text{Incident Radiation Bandwidth}}$

#### 9-2.3 SUB-CASE C

Now assume we have an incident radiation spectrum of Fig. 9-6. This important case is a rough piecewise linear generalized approximation for the sun's power spectral density..

What is  $\eta_{\max}$  for the EWEC converter as a function of converter bandwidth?

The incident power is

$$P_1 = AI_o = A \int_0^{\infty} I(\lambda) d\lambda = A \left[ \frac{1}{2} A_o (\lambda_3 - \lambda_2) + A_o (\lambda_4 - \lambda_3) + \frac{1}{2} A_o (\lambda_5 - \lambda_4) \right]$$

$$= AA_o \left[ \frac{\lambda_4 + \lambda_5}{2} - \frac{\lambda_2 + \lambda_3}{2} \right]$$

$$(5) \quad P_1 = AA_o B_1$$

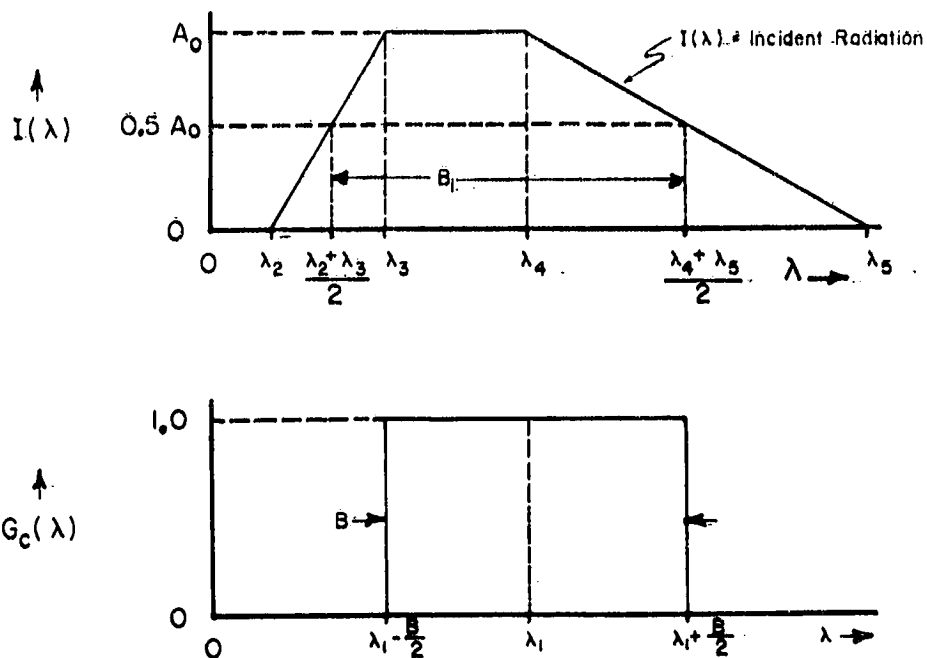


FIG. 9-6 A generalized piecewise linear approximation of the sun's power spectral density irradiating an EWEC converter with bandwidth  $B$  centered on  $\lambda_1$ .

Eq. (5) suggests that the sun's assumed irradiance curve in Fig. 9-6 is roughly equivalent to that shown in Fig. 9-7. Both curves have a bandwidth

$$(6) \quad B_1 = \left( \frac{\lambda_4 + \lambda_5}{2} \right) - \left( \frac{\lambda_2 + \lambda_3}{2} \right)$$

The equivalent  $I(\lambda)$  is centered on the mean wavelength,  $\lambda_m$ , of the original power spectral density curve or

$$(7) \quad \lambda_m = \frac{1}{4} (\lambda_2 + \lambda_3 + \lambda_4 + \lambda_5)$$

With the recognition of the equivalence idea, this case reduces to Sub-Case B above where it was shown desirable to have  $B \geq B_1$  for maximum converter efficiency. The converter passband should be tuned

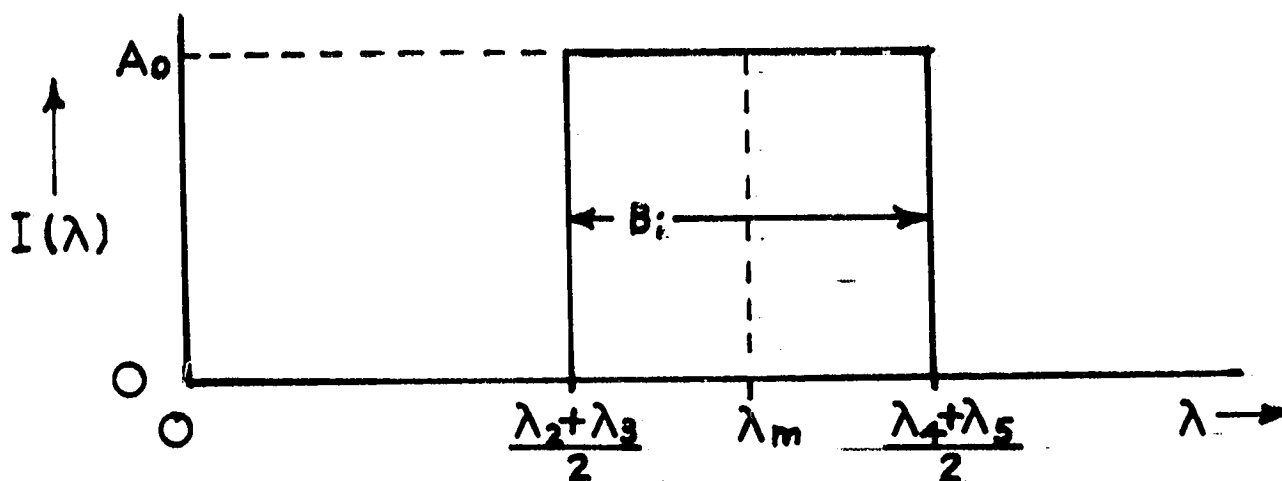


FIG. 9-7 Power spectral density curve roughly equivalent to the more complex one for the sun in Fig. 9-6.

to  $\lambda_1 = \lambda_m$ .

The result is that the curve of  $\eta_{\max}$  for this sub-case is the same as Fig. 9-5. It is all the clearer now, however, that to achieve the highest theoretical converter efficiency for solar-electric or solar thermal conversion, ideally (1) the EWEC converter bandwidth must equal that of the sun's equivalent power spectral density curve for the irradiation arriving at the converter, and (2) that the converter's overall power gain curve should be centered on the mean solar spectral wavelength,  $\lambda_m$ . Since the sun's spectrum at the earth's surface is roughly from 0.3 to 1.1 micrometers [65] the EWEC converter should be centered approximately at: —

$$\lambda_m = 0.7 \text{ micrometers —}$$

$$B = 0.8 \text{ micrometers}$$

These figures represent a fractional bandwidth  $B/\lambda_m$  of 1.14 for the converter. Whether such a fractional bandwidth can, in fact, be achieved with EWEC converter elements of a single length remains to be determined by subsequent research. If it can, then there appears no fundamental external reason why converter efficiencies approaching 100% cannot be built. Naturally realistic efficiencies will be less because of internal absorber and rectification losses.

### 9-3 CASE II ANALYSIS

#### The Problem

Sub-case C above indicated the need for large fractional bandwidths of the EWEC converter when operated as an efficient solar-electric converter. In the event such fractional bandwidths are not subsequently achievable with converter elements of a single length, it is instructive to investigate the theoretical possibility of using multiple length absorber elements. The first obvious step is consideration of two lengths of absorber elements.

What  $\eta_{\max}$  could be expected for this configuration?

The model to be analyzed is shown in Fig. 9-3.

#### Assumptions

1.  $L_{20} > L_{10}$ , hence implies converter elements in area  $A_{10}$  centered on a shorter spectral wavelength than those in area  $A_{20}$ .
2. Each Area has a passbandwidth,  $B_{10}$  and  $B_{20}$ , associated with it. Obviously this means the fractional bandwidths for each area won't be the same.
3. No Overlapping of passbands for the two areas.
4. Each Element passband is centered somewhere within the incident irradiation band.
5. The Two Lengths of absorber elements occupy arbitrary fractional parts of the total absorber area. The possibility of



interspersing the two lengths of elements is also recognized based on observations of insect antennae. This more complex case has too many unknowns to concern us in this early analysis, however. What advantages interspersing as in nature<sup>1</sup> other than a means of increasing bandwidth may have are not known at this time.

6. The Incident Spectrum (sun) is approximated as in sub-case C, Fig. 9-7.

#### The Macroscopic Model

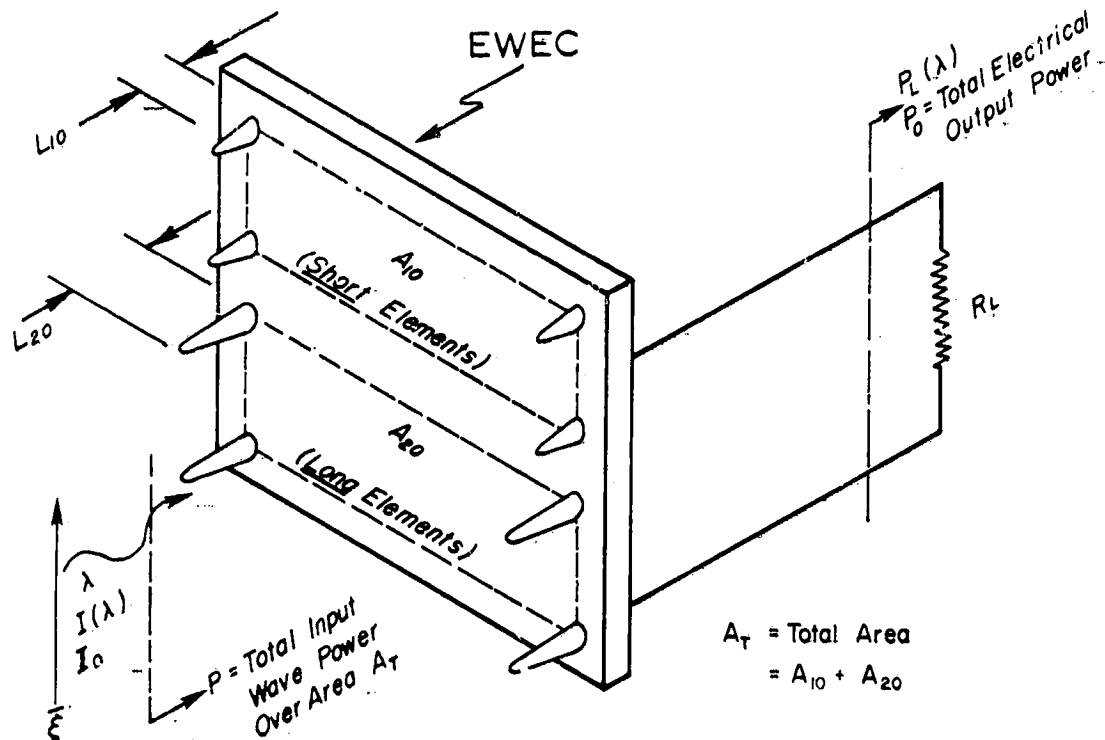


FIG. 9-8 First-order macroscopic model for Electromagnetic Wave Energy Converter with two lengths of absorber elements dispersed over the total area.

<sup>1</sup>Insect antennae again! It is interesting to observe that the successful solar-thermal EWEC-like absorber created by Cumo, et al [31] of IBM had this same idea with  $L_{20}$  40-60 $\mu$ m and  $L_{10}$  of 10 $\mu$ m average. They call the arrangement "a dense forest" with "underbrush." They also observe "This double dendrite structure may be responsible for the very large wavelength range of absorption." (0.5-40 $\mu$ m). No theoretical explanation was advanced, however.

### Analysis

The analysis procedure is generally similar to that of Case 1.

The incident power is

$$P_i = A_i A_o B_i = (A_{10} + A_{20}) A_o B_i$$

To find the output power we use Fig. 9-9.

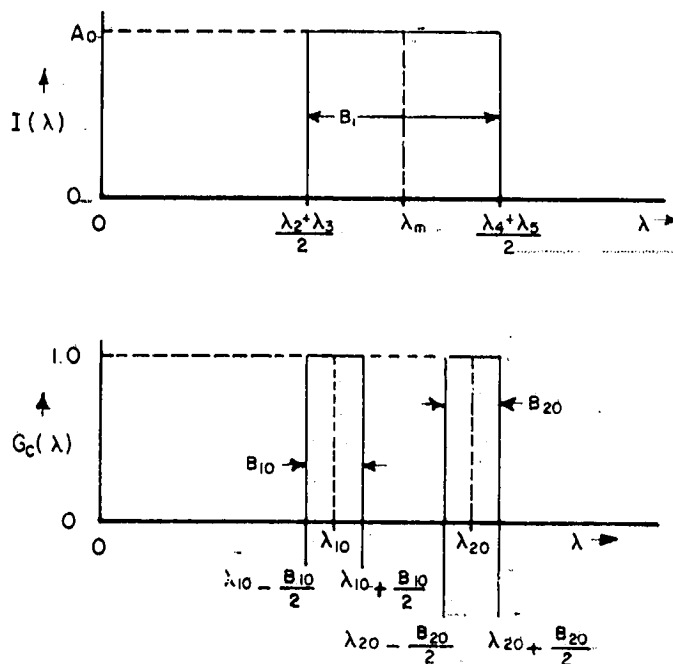


FIG. 9-9 (Upper) Rough equivalent of the sun's power spectral density (from sub-case C).— (Lower) Assumed power gain for the two element EWEC converter. The  $I(\lambda)$  in the upper sketch simultaneously irradiates both converter areas.

The maximum converter output power from area  $A_{10}$  is

$$P_{o10} = A_{10} \int_0^{\infty} P_{L10}(\lambda) d\lambda = A_{10} \int_0^{\infty} G_{c10}(\lambda) I(\lambda) d\lambda$$

$$= A_{10} \int_{\lambda_{10} - \frac{B_{10}}{2}}^{\lambda_{10} + \frac{B_{10}}{2}} A_o d\lambda = A_{10} A_o B_{10}$$

Similarly the maximum converter output from area  $A_{20}$  is

$$P_{o20} = A_{20} A_o B_{20}$$

The total array output power is simply that from the two areas or

$$\begin{aligned} P_o &= P_{o10} + P_{o20} = A_{10} A_o B_{10} + A_{20} A_o B_{20} \\ &= A_o (A_{10} B_{10} + A_{20} B_{20}) \end{aligned}$$

The maximum converter efficiency when irradiated with the assumed sun's equivalent  $I(\lambda)$  is

$$\begin{aligned} \eta &= \frac{P_o}{P_i} = \frac{A_o (A_{10} B_{10} + A_{20} B_{20})}{A_o (A_{10} + A_{20}) B_i} \\ (8) \quad \eta &= \left( \frac{A_{10}}{A_T} \right) \frac{B_{10}}{B_i} + \left( \frac{A_{20}}{A_T} \right) \frac{B_{20}}{B_i} \end{aligned}$$

Eq. (8) is quite general and is the result sought. Note that it reduces to Eq. (4) if either  $A_{10}$  or  $A_{20} = 0$ , as expected since the absorbers are then all of a single length.

If we now assume  $A_{10} = A_{20}$ , i.e. each occupies one-half the total converter area, then Eq. (8) shows

$$\eta = 0.5 \frac{B_{10}}{B_i} + 0.5 \frac{B_{20}}{B_i}$$

If we further invoke assumption (3) above while simultaneously requiring that both bandwidths be equal and  $B_{10} + B_{20} = B_i$ , then

$$\eta = 0.5 \times 0.5 + 0.5 \times 0.5$$

$$(9) \quad \eta = 50\%$$

It is immediately clear that the reason the converter's efficiency is no higher is because each area is absorbing, at most (when it has  $B = B_1/2$ ), only half the input power spectral density because of the assumed bandwidth limitation of each length absorber element. If larger fractional bandwidths can, in fact, be achieved for each absorber area, then converter efficiency will theoretically increase proportionally. Overlapping of absorber passbands would also appear to increase the conversion efficiency. Obviously this possibility as well as the optimum location of  $\lambda_{10}$  and  $\lambda_{20}$  for the actual sun's spectrum should be theoretically examined in subsequent research along with determining the maximum fractional bandwidths achievable for operable absorbers. Then the whole more complex proposition of incoherent and randomly polarized  $\vec{E}$  field irradiation should also be theoretically researched.

The Result is that Eq. (8) defines the basic theoretical maximum EWEC converter efficiency under the stated assumptions. If large absorber fractional bandwidths are not achievable with a single length absorber cone or pyramid design, then the alternative is two lengths of absorber elements each with a smaller but probably achievable bandwidth.

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<sup>1</sup>Three or more lengths are also obviously possible but appear less desirable from both converter efficiency and later manufacturing standpoints.

It is further clear that with some overlapping of absorber passbands the maximum efficiency could exceed 50%, reaching 100% if each element's bandwidth 'matches' that of the equivalent sum. But then the case would have merged to be identical to the single length absorber case treated earlier!

It is also clear that whether one uses a single length absorber element (preferred if the required fractional bandwidth is achievable) or two lengths the maximum theoretical EWEC conversion efficiency appears so much higher than that of the conventional silicon solar cells 15 percent efficiency as to make it worth striving for.

Finally, we recognize this early crude theoretical analysis could be refined later to include non-idealized passbands, overlapping and other detailed effects.

## Chapter 10

### DISCUSSION OF RESEARCH RESULTS

Insects And Electromagnetic Waves. This research let us accumulate, study, summarize, and coherently organize a large body of existing scientific research knowledge on insect navigation and communication means via electromagnetic waves. Additionally, we found it essential to extend present scientific knowledge to the detailed electro-optics and probable operation of a single insect dielectric antenna spine by advancing an hypothesis for explaining its operation. It appears to fit presently known facts in both entomology and electromagnetics. It is clear that understanding the single spine well is the foundation on which later more quantitative theoretical research can safely be built.

This important theoretical work has, in a broad sense, only begun. The understanding therefrom will benefit both entomologists and their concern for electrical control of insects as well as EWEC technology. Unfortunately, the grant period was too short to get the summary of this work published as originally planned. Instead it was incorporated herein (Chap. 5). We are hopeful of publishing it later.

The structural similarities of the marvelous antennae found on insects (Chap. 5) and the type absorbers proposed for man-made EWEC absorbers (Chap. 2) are now so strong and so thoroughly documented (Chap. 4 and elsewhere) that we no longer have even the slightest doubts about the general validity of the EWEC concept as being a worthy direction for solar advanced research to pursue. The well-known philosophy of 'learning from Nature' appears -- once again --

vindicated and, in our judgment, is exceptionally pertinent to EWEC research. It lends more than rhetorical credence to the notion that "The insects may point us out of the energy crisis" if we correctly interpret the operation of their antennae and aggressively follow-up the indicated EWEC research.

But we are well aware of the limitations of this analogical thinking between Nature's structures and man-made EWEC converters. There is a point beyond which Nature's analogies cannot be pressed except in a very general way. One of these lies in the large surface areas inherent to man-made EWEC solar converters. Such converters would involve many billions of spines whereas considerably smaller numbers are to be found on insects because of their small size and the fact their antennae appear primarily designed as signal converters instead of power converters as EWEC research seeks. There is also the limitation of the rectification means used in nature in the insect antennae to get the electrical signal into the insect's nerve. While our present knowledge of the details of the biological converter used in Nature<sup>1</sup> are considerably less than satisfactory, it is evident that it is most probably optimized for best signal-to-noise ratio, as Van Der Ziel's [75] early work indicates, and not for maximum power conversion efficiency as would be necessary for the rectification means on man-made EWEC power converters.

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<sup>1</sup>We have hypothesized that rectification may be a result of long chain molecules forming the ultimate in cat's whisker point contacts. We briefly explored this notion, but it is too early to include it herein.

Some will undoubtedly argue that the insights achieved into insect antenna operation during the course of this research grant are, once explained (Chap. 5), rather obvious to those skilled in electromagnetics. Such critics use the well-known wisdom of 20-20 hindsight and fail to realize both the difficulty of original research and that practitioners of electromagnetics largely have not heretofore been disposed to explore insect antennae any more than entomologists -- in the main, other than Callahan -- have been disposed to explore electromagnetics. Nor have solar engineers -- in the main -- heretofore seen either field as relevant to what they are attempting to achieve!

All these initial insights are indicative of the interdisciplinary nature inherent to such advanced energy research.

The Metal And Dielectric Theoretical Models were explicitly formulated, for the first time, in this research (Chaps. 6 and 7). A careful study of Figs. 6-1, 6-2, 7-1, and 7-2 reveals large areas of inherent commonness -- not heretofore appreciated -- between radiant-thermal and radiant-electric absorbers of the general EWEC type. We now see these as sub-cases of the larger physics field of wave-surface interactions (Chap. 4) where the morphology of the surface is deliberately designed to achieve a specific result, e.g. solar-thermal absorption. A part of this new insight lies in recognizing the notion that solar-thermal and solar-electric absorbers are theoretically linked and are part of a continuum of wave-surface interactions on rough surfaces.

It appears this grant's research is but the first step toward a fuller more complete theoretical understanding of such wave-surface



absorption interactions. We believe it could lead eventually to:

- Better Solar Absorptivity Surfaces by controlling the material and surface morphology, thus 'tuning' the surface to the incident spectrum.
- Higher Absorptivity/Emissivity surfaces for metals by preselecting the spine lengths correctly in relation to the wavelengths to be absorbed while simultaneously minimizing the antenna's ability to reradiate at much longer wavelengths.
- Practical Dielectric Absorber Elements for high efficiency solar-electric conversion.

It had been our initial hope to rigorously analyze these models starting from Maxwell's equations; but such a venture proved much too ambitious for the short 6 month grant period. Instead we opted for performing a careful definition of the explicit technical problems which are now known (Chaps. 6 and 7) for the first time. Hopefully the orderly analysis can now proceed in follow-on research. It is recognized the analysis is a formidable theoretical undertaking.

The Rough Efficiency Comparisons made in Chap. 8 were most revealing -- even if they are only approximate estimates. The comparison showed, for the first time, we believe, a semi-plausible theoretical basis for why metals<sup>1</sup> are probably best for radiant thermal converters -- a fact long known to solar thermal engineers but not well understood -- whereas dielectrics appear more promising for absorbers to be used for later radiant-electric purposes. It is now clear, however, -- thanks to the early work done by Bell Labs on dielectric antennas at microwave

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<sup>1</sup>The success of Cuomo [31], et al at IBM with EWEC-like metallic surfaces is a case in point.

2.2  
frequencies -- that for the latter purpose the dielectric material must be selected with care to have a minimum loss tangent in the-wave-length range being received if conversion efficiency,  $\eta$ , is to be maximized.

It appears, based on these rough estimates -- which must be -- verified by later more quantitative theoretical 'field' approaches -- that EWEC dielectric absorbers having an efficiency of over 90 percent (a conservative estimate if the dielectric material is carefully chosen) could, in principle, be created for the solar wavelength range.

The high expected efficiency of EWEC dielectric absorbers coupled with the high efficiencies theoretically attainable when the absorber bandwidth equals or exceeds that of the radiant spectrum (Chap. 9) strongly suggests that the dielectric absorbers are not a fundamental limitation to eventually creating a successful high efficiency solar-electric converter even though we do not yet know the detailed design equations for making EWEC structures to prescribed specifications.

The principal limitation to the EWEC invention may well be the rectification means -- a subject which we recognized some years ago but was beyond the scope of this short grant. However, Javan [43], Gustafson [37], Van Der Ziel [75], and others have done early research in this direction. Additional research on the general problem of how to rectify the electrical output of the EWEC dielectric spines is clearly needed.

The Research Goals In summary, at this point in time we have strong indications from this research that for an EWEC solar-electric

converter:

- Material -- Should probably be low loss dielectric.
- Geometry -- Tapered hollow conic in the range of about  $6 \lambda$  long.
- Losses -- Not greater than 10 percent of the irradiation if the absorber material is chosen for minimum loss in the solar range.
- Center Freq. -- -- Prediction awaits later analysis. It is very clear, however, to us that the absorber length must be tuned to the mean wavelength of the irradiating spectrum.
- Bandwidth -- A theoretical first-order model has been formulated and analyzed (Chap. 9), giving considerable new insights.
- Beamwidth -- No advancement made in this area.
- Array Spacings -- The theoretical models proposed (Chaps. 6 and 7) encompass all the cases likely to be of any later practical importance from close-packed to wide-spaced periodic structures.  
  
Though not analytically yet solved, the explicit problem definition of Chap. 7 is a substantial step achieved which had not been done heretofore.
- Conversion Efficiency -- Conservative estimates are 90 percent for dielectric absorber structures alone if it is chosen so it is tuned to the irradiating spectrum and also has a matching bandwidth. If a fractional bandwidth of only 0.5 can be achieved, then the absorber efficiency would

decrease to the 45-50 percent range -- still much above the 15 percent of the silicon solar cell. The losses in the rectification means would decrease these figures an unknown amount.

Clearly the research goals outlined in Chap. 3 were only about 70-80 percent achieved, the grant period being too short and only part-time work involved by all personnel. Nevertheless, overall, we believe it fair to say this short austere grant has made it possible to substantially strengthen the scientific basis for the EWEC concept, and this was the principal general goal; but much more theoretical research yet remains to be done before the EWEC concept is understood to the point specific radiant-electric hardware can be designed and built that will in fact work in the solar wavelength range.

## Chapter 11

### CONCLUSIONS

Based on the evidence accumulated during this short preliminary theoretical research we conclude that:

1. The Importance of Direct Conversion Advanced Research for both radiant-thermal and radiant-electric cases appears established in light of the Nation's larger energy problems (Chap. 1).

A market potential in the range of billions of dollars is seen for a successful low cost solar-electric converter -- a considerable incentive in addition to the great beneficial relief from exhausting our fossil fuels which such a converter would tend toward.

2. The Electromagnetic Wave Energy Converter Concept is clearly another major new research option -- in addition to conventional solar cells -- open to those in the research community who continue to believe high efficiency direct conversion to electricity can eventually be achieved without resorting to thermal cycles and their limitations.
3. The Scientific Basis for the EWEC concept is now on a substantially firmer basis than when this research grant began.
4. The Potential Advantages of EWEC envisioned in Chap. 2 appear reinforced in that:

- Δ Absorber Efficiency of about 50 percent or more appears easily theoretically possible under the assumptions made.
- Δ Function Separation Capability, i.e. the ability to separate absorption means from rectification means inherent to the EWEC concept, appears continued valid. This research only preliminarily examined the absorption problem, however, and little attempt was made to explore rectification.
- Δ Power Spectrum Matching Capability of EWEC is greatly reinforced both from the insect research (Chap. 5) and from theoretical considerations (Chap. 9).

A. The Other Advantages were not explored in this research.

5. Understanding Insect Absorbers of electromagnetic waves in the infrared wavelength range, especially of single poly-tubular dielectric spines, point toward sensible directions for future engineering research on EWEC converters. This large body of scientific knowledge, as it bears on EWEC research, was brought together, documented, and coherently organized for the first time (Chap. 5).
6. Radiant-Thermal and Radiant-Electric absorbers are now seen as both related theoretically and sub-parts of the larger physics field of electromagnetic wave-surface interactions. This field was summarized and coherently organized for the first time (Chap. 4) to our knowledge. Substantial mathematical-physics prior work has been done in this field; but such theoretical work largely has not been directed toward the utilitarian ends sought in EWEC research, i.e. the creation of better man-made solar-thermal and solar-electric converters.
7. Explicit Technical Models have now been formulated (Chaps. 6 and 7) for the first time and thoroughly justified. The mathematical boundary value problems they pose have not, however been solved. These important models define the technical heart of the EWEC concept for the two important cases of metallic and dielectric materials. The dielectric case appears to be the most technically complex case.
8. Metals vs Dielectrics were examined roughly in Chap. 8. It preliminarily appears that metals are best for radiant-thermal conversion whereas dielectrics appear more promising for radiant-electric converters. We further conclude that, conservatively, EWEC dielectric absorbers alone if made of low loss dielectric material could have efficiencies in excess of 90 percent in the solar spectral range.
9. The Bandwidth of EWEC absorbers is an important theoretical constraint, it being found desirable to have the absorber both tuned to the incident spectrum as well as, ideally, matching its bandwidth. Fractional bandwidths greater than 0.5 are desirable.

This research indicates the preliminary technical feasibility -- on a broad basis -- of the EWEC concept. No major technical flaw

turned up in the basic concept. To this end these results have been most encouraging, tending to verify earlier expectations for the invention.

It is too early, however, in this research to conclude that the overall technical feasibility of the EWEC concept is definitely proven, as many major theoretical aspects yet need to be examined more carefully.

## Chapter 12

### RECOMMENDATIONS

It is abundantly clear from this report that substantial more scientific and engineering research is needed on EWEC before its potential advantages can be realized.

To continue advancing this important early EWEC research, we recommend that:

1. An Ongoing Research Program on EWEC be initiated.

Without it progress will stop and a practical high efficiency low cost direct solar-electric converter -- beyond classical solar cells -- may never be created.

2. The Research Thrusts be in the areas of: —

- a. Scientific Research should continue in the general area of the electro-optics of insect antennas.

Such work has been concretely shown to yield benefits extremely useful in both science and engineering areas.

To be most beneficial, such scientific work should occur in the general areas of:

- Δ Studying the insect antennae material compositions more closely as a check on the hypotheses advanced in Chap. 5.
- Δ Exploring the coupling probes in more detail than heretofore.
- Δ Exploring the rectification means used in Nature, i.e. how the spine's output is converted to an electrical signal -- without semiconductors -- at the nerve output of the sensilla.

- b. Engineering Theoretical Analysis of:

The 'metal' and 'dielectric' EWEC models



explicitly formulated and justified in this report.

Once solved, the analysis should be extended to the 3-dimensional case as well as to statistically varying absorber lengths, as these will be of later importance in practically fabricated EWEC surfaces (solar-thermal) and converters (solar-electric).

- A The important problem of the EWEC converter irradiated with non-isotropic stochastic electromagnetic fields as the sun emanates.

This research would permit EWEC modeling to progress beyond the present plane wave classical case toward more realistic solar waves..

- c. A Microwave Experimental Program be initiated aimed at constructing and checking the general validity of dielectric absorber arrays of EWEC type shown in Fig. 7-1 and 7-2.

Such experimental work, if well planned and executed, could profitably guide both the future theoretical and materials research. The results in the microwave range where experimentation is tractable could later be scaled to the solar range.

- d. Studying The Power Rectification Problem for EWEC in a creative preliminary way.

This early work would involve summarizing the prior solid state physics work in-depth and probably creatively exploring new means for rectifying in the 0.3 - 1.5 $\mu$ m wavelength range. This work might also involve extending some of the long chain organic molecule rectification ideas created during the present grant (but not reported herein in-depth).

The eventual success of an EWEC solar-electric converter hinges on solving the rectification problem in a technically efficient, practical, manufacturable way.

c. Materials Research should be initiated on:

- A EWEC-like metallic surfaces at solar wavelengths intended for solar-thermal conversion uses.

This effort would be experimental in nature.

It is too early to initiate experimental research on dielectric surfaces except at microwaves.

A Dielectric materials with the aims of:

1. Exploring whether a material technology exists for making large area dielectric spiny surfaces. If not, can it be created? What favorable prior art exists? —
2. Exploring material and processing problems likely to be encountered in developing a practical technology for fabricating EWEC absorbers, assuming the theoretical analysis recommended in 2-b continues to appear favorable.

It is clear that the recommended advanced research is strongly interdisciplinary in nature and, if pursued, must be with this philosophy.

#### ACKNOWLEDGMENT

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The interest of Dr. A. Van Der Ziel in EWEC research has been a source of encouragement to us. Our discussions with this great researcher and scholar have been most helpful.

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#### REFERENCES

1. Bailey, Robert L., U. S. Patent No. 3,760,257, issued Sept. 18, 1973. (Assigned to NASA under Fletcher's name.)
2. Bailey, Robert L., "Electromagnetic Wave Energy Conversion," NASA Technical Memorandum No. NASA TM-X-62,269, Proceedings of NASA Laser-Energy Conversion Conference, Moffet Field, CA., Jan. 18-19, 1973. (Copies: Dr. Kenneth W. Billman, NASA Ames Research Center, Moffet Field, CA. 94035.)
3. Bailey, R. L., "A Proposed New Concept for a Solar-Electric Converter," ASME Journal of Engineering For Power, April 1972, pp. 73-77.
4. Bailey, Robert L., Research Notes while at Goddard Space Flight Center, Summer, 1968 (unpublished).
5. Beckman, Petr and Spizzichino, André, The Scattering of Electromagnetic Waves from Rough Surfaces, [New York; MacMillan, 1963].
6. Bernard, Gary D. and Miller, William H., "What Does Antenna Engineering Have to Do With Insect Eyes?", IEEE Student J., Jan-Feb 1970, pp. 2-8.
7. Bernhard, C. G., "Structural and Functional Adaptation in a Visual System," Endeavour, Vol. 29, (1967), pp. 79-84.
8. Brown, William C., "Satellite Power Stations: A New Source of Energy?", IEEE Spectrum, Vol. 10, No. 3, March 1973, pp. 38-47.
9. Brown, W. C., "Progress in the Design of Rectennas," J. Microwave Power, Vol. 4, 1969, pp. 168-175.
10. Callahan, Philip S., Tuning into Nature -- Solar Energy, Infrared Radiation, and the Insect Communication System, [New York, N. Y.; Devin-Adair Pub. Co., (in press)].
11. Callahan, Philip S., "Insect Antennae with Special Reference to the Mechanism of Scent Detection and the Evolution of the Sensilla," Int. J. Insect Morphol. & Embryol., 4(1): C00-000, Pergamon Press, 1975.
12. Callahan, Philip S., "Laser in Biology," Laser & Elektro-Optik, Vol. 2, June 1975, pp. 38-39.
13. Callahan, P. S. and Lee, F., "A Vector Analysis of the Infrared Emission of Night Flying Moths with a Discussion of the System as a Directional Homing Device," Ann. Entomol. Soc. Amer., 67(3), 1974, pp. 341-55.

# REFERENCES (Cont'd.)

14. Callahan, P. S., "Studies on the Shootborer, Hypsipla grandella (Zeller) (Lep. Pyralidae). XIX. The Antenna of Insects as an Electromagnetic Sensory Organ," Turrialba, 23(3), 1973, pp. 263-74.
15. Callahan, P. S. and Carlisle, T. C., "A Function of the Epiphysis on the Foreleg of the Corn Earworm Moth, Heliothis Zea," Ann. Entomol. Soc. Amer., 64(1), 1971, pp. 309-11.
16. Callahan, P. S., "Far Infrared Stimulation of Insects with the Glagolewa-Arkadiewa Mass Radiator," Fla. Entomol., 54(2), 1971, pp. 201-04.
17. Callahan, P. S., "Insects and the Unsensed Environment," 1971, pp. 85-96. In R. Komarek (ed.), Proc. Tall Timbers Conf. on Ecol. Animal Control by Habitat Management, Tallahassee, FLA.
18. Callahan, P. S., "Insects and the Radiation Environment," 1970, pp. 247-58. In R. Komarek (ed.), Proc. Tall Timber Conf. on Ecol. Animal Control by Habitat Management, Tallahassee, FLA.
19. Callahan, P. S., "The Exoskeleton of the Corn Earworm Moth, Heliothis Zea (Lepidoptera: Noctuidae) with Special Reference to the Sensilla as Polytubular Dielectric Arrays," Univ. of Ga. Agric. Exp. Sta. Res. Bull., No. 54, 1969, pp. 5-105.
20. Callahan, P. S., "A High Frequency Dielectric Waveguide on the Antennae of Night-Flying Moths (Saturnidae)," Applied Optics, Vol. 7, August 1968, pp. 1425-1430.
21. Callahan, P. S., "Insect Molecular Bioelectronics: A theoretical and Experimental Study of Insect Sensillae as Tubular Waveguides with Particular Emphasis on their Dielectric and Thermoelectric Properties," Misc. Pub. Ent. Soc. Am., 5(7), 1967, pp. 313-47.
22. Callahan, P. S., "Electronic Instrumentation for Infrared and Microwave Studies of Insect Communication Systems," Proc. 19th Annu. Conf. Eng. Med. Biol., San Francisco, CA., 225, 1966, p. 157.
23. Callahan, P. S., "A Photoelectric-Photographic Analysis of Flight Behavior in the Corn Earworm Heliothis Zea, and Other Moths," Ann. Ent. Soc. Am., 58(2), 1965, p. 727.
24. Callahan, P. S., "Intermediate and Far Infrared Sensing of Nocturnal Insects, Part I. Evidences for Far Infrared (FIR) Electromagnetic Theory of Communication and Sensing in Moths and its Relationship to the Limiting Biosphere of the Corn Earworm," Ann. Entomol. Soc. Amer., 58, 1965, pp. 727-45.

# REFERENCES--(Cont'd.)

25. Callahan, P. S., "A Photographic Analysis of Moth Flight Behavior with Special Reference to the Theory for Electromagnetic Radiation as an Attractive Force Between the Sexes and to Host Plants," Proc. XII Int. Congr. Entomol., London, 5, 1964, p. 302.
26. Callahan, P. S., "Behavior of the Imago of the Corn Earworm, Heliothis Zea (Boddie), with Special Reference to Emergence and Reproduction," Ann. Entomol. Soc. Amer., 51(3), 1958, pp. 271-83.
27. Childers, D. G., "Antenna Reception of Nonisotropic Stochastic Fields," J. of the Franklin Institute, Vol. 282, No. 4, October 1966, pp. 216-230.
28. Cherepanov, A. K., "Reflection of Electromagnetic Waves from an Absorptive Spiky Surface," Elektronika, Vol. 19, August 1974, pp. 1749-53. In Russian. Translation available through No. Carolina Science & Tech. Research Center, No. A74-43090.
29. Clapham, P. B. and Hutley, M. C., "Reduction of Lens Reflection by the 'Moth Eye' Principle," Nature, Vol. 244, August 3, 1973, pp. 281-282.
30. Cone, D. R., Stanford Research Institute, private communication to Professor R. L. Bailey.
31. Cuomo, J., Ziegler, J. F. and Woodall, J. M., "A New Concept for Solar Energy Thermal Conversion," Applied Physics Letters, 15 May 1975.
32. Davies, J. Brian, "A Least-Squares Boundary Residual Method for the Numerical Solution of Scattering Problems," IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-21, No. 2, Feb 1973, pp. 99-104.
33. DiDomenico, Jr., Mauro, "Wires of Glass," Industrial Research, August (1974), pp. 50-54.
34. Drexhage, Karl H., "Monomolecular Layers and Light," Scientific American, March 1970, pp. 108-119.
35. Fang, D. J., "Scattering From a Perfectly Conducting Sinusoidal Surface," IEEE Transactions on Antennas and Propagation, May 1972, pp. 388-390.
36. Féry, M. C., "Propriétés Sélectives Des Corps Noirs Employés Comme Récepteurs Dans La Mesure De L'Énergie Rayonnante Et Conséquences Qui En Decoulent," J. de Phys., 8:1909, 758-70.

# REFERENCES (Cont'd.)

37. Gustafsson, Kenneth, "Optical Diodes," NASA Technical Memorandum No. NASA TM-X-62, 269, Op. Cit.
38. Harrington, Roger F., "Matrix Methods for Field Problems," Proc. of the IEEE, Vol. 55, No. 2, Feb. 1967, pp. 136-149.
39. Haynos, J., et al., "The Comsat Non-Reflective Silicon Solar Cell: A Second Generation Improved Solar Cell," presented at Int'l Conf. on Photovoltaic Power Generation, Hamburg, Germany, Sept 25-27, 1974.
40. Heller, Wilfred, "Theoretical Investigations on the Light Scattering of Spheres. XVI. Range of Practical Validity of the Rayleigh Theory," The J. of Chemical Physics, Vol. 42, No. 5, March 1, 1965, pp. 1609-1615.
41. Hsiao, Henry S., Susskind, Charles, "Infrared and Microwave Communication by Moths," IEEE Spectrum, March 1970, pp. 59-76.
42. Ikuno, Hiroyoshi and Yasuura, Kamenosuke, "Improved Point-Matching Method with Application to Scattering from a Periodic Surface," IEEE Transaction on Antennas and Propagation, Vol. AP-21, No. 5, Sept 1973, pp. 657-662.
43. Javan, Ali, "Optical Diodes," NASA Technical-Memorandum, No. NASA TM-X-62, 269, Op. Cit.
44. Kerker, M., et al., "Light Scattering from Infinite Cylinders. The Dielectric-Needle-Limit," J. Opt. Soc. Amer., 60(9), Sept 1970, pp. 1236-39.
45. Kerker, M., Cooke, D. Farone, W. A. and Jacobsen, R. A., "Electromagnetic Scattering from an Infinite Circular Cylinder at Oblique Incidence. I. Radiance Functions for  $m = 1.46$ ," J. of the Optical Society of America, Vol. 56, No. 4, April 1966, pp. 487-491.
46. Kiely, D. G., Dielectric Aerials, [London: Methuen, 1953].
47. Koltun, M. M., "Selective Coating with a Variable Ratio of Integral Optical Coefficients," Geliotekhnika (Applied Solar Energy, USSR), Vol. 8, No. 5, 1972, p. 38.
48. Lee, Shung-Wu, "Electromagnetic Reflection from a Conducting Surface: Geometrical Optics Solution," IEEE Trans. Antennas and Propagation, Vol. AP-23, No. 2, March 1975, pp. 184-190.

REFERENCES (Cont'd.)

49. Mahan, A. I., "Far-Field Diffraction and Bore-sight Error Properties of a Two-Dimensional Wedge," J. Opt. Soc. Amer., 49(6), June 1959, pp. 535-56.
50. Matarrese, L. M. and Evenson, K. M., "Improved Coupling to Infrared Whisker Diodes by Use of Antenna Theory," Appl. Phys. Letters, Vol. 17, No. 1, July 1, 1970, pp. 8-10.
51. McKinney, Jr., Chester M., "Dielectric Waveguides and Radiators," Clearinghouse for Federal Scientific and Technical Information (unclassified) #AD 634 792, Dissertation for Degree of Doctor of Philosophy, University of Texas (1950).
52. Meecham, W. C., "Variational Method for the Calculation of the Distribution of Energy Reflected from a Periodic Surface. I.," J. of Appl. Phys., Vol. 27, No. 4, April 1956, pp. 361-367.
53. Millar, R. F., "The Rayleigh Hypothesis and a Related Least-Squares Solution to Scattering Problems for Periodic Surfaces and Other Scatterers," Radio Science, Vol. 8, No. 8, 9, Aug-Sept 1973, pp. 785-796.
54. Millar, R. F., "Singularities of Two-Dimensional Exterior Solutions to the Helmholtz Equation," Proc. Camb. Phil. Soc., Vol. 69, (1971), pp. 175-188.
55. Millar, R. F., "On the Rayleigh Assumption in Scattering by a Periodic Surface. II.," Proc. Camb. Phil. Soc., Vol. 69, (1971), pp. 217-225.
56. Millar, R. F., "On the Rayleigh Assumption in Scattering by a Periodic Surface," Proc. Camb. Phil. Soc., Vol. 65, (1969), pp. 773-791.
57. Mueller, G. E. and Tyrrell, W. A., "Polyrod Antennas," Bell Syst. Tech. J., Vol. 26, (1974), pp. 837-851.
58. Mueller, G. E., "Microwave Directive Antenna," United States Patent Office, Aug 12, 1947, No. 2,425,336.
59. Ornstein, L. S. and Van Der Burg, A., "Reflectivity of Corrugated Surfaces," Physica, Vol. IV, No. 11, Dec 1937, pp. 1181-1189.
60. Peak, H. J., NASA, GSFC, Private Communications to Prof. R. L. Bailey, Nov 21, 1974.



# REFERENCES (Cont'd.)

61. Ramon, Simon and Whinnery, John R., Fields and Waves in Modern Radio, Second Edition, [New York, N. Y.: John Wiley & Sons, Inc., 1953].
62. Rawson, Eric G., "Theory of Scattering by Finite Dielectric Needles -- Illuminated Parallel to Their Axes," J. of the Optical Society of America, Vol. 62, No. 11, Nov. 1972, pp. 1284-1286.
63. Rayleigh, Lord, "On the Dynamical Theory of Gratings," Proceedings of the Royal Society, Series A79 (1907), pp. 399-416.
64. Rayleigh, Lord, "On the Passage of Electric Waves through Tubes, or the Vibrations of Dielectric Cylinders," Phil. Mag. S. 5., Vol. 43, No. 261, Feb 1897, pp. 125-32.
65. Robinson, N., Solar Radiation [New York, N. Y.: American Elsevier Publishing Co., Inc., 1966].
66. Santala, Teuvo, "Intermetallic Absorption Surface Material Systems for Collector Plates," Proceedings of the Workshop on Solar Collectors for Heating and Cooling of Buildings, Nov. 21-23, 1974, pp. 233-235.
67. Seraphin, B. O., "Selective Surfaces for Photothermal Solar Energy Conversion Manufactured by Chemical Vapor Deposition," Workshop Proceedings, Photovoltaic Conversion of Solar Energy for Terrestrial Applications, Vol. II, Invited Papers, Oct 23-25, 1973, pp. 80-81.
68. Sinor, T. B. A., "The Scattering of Electromagnetic Waves by a Corrugated Sheet," Canadian J. of Physics, Vol. 37, No. 7, July 1959, pp. 787-797, and Correction in Letter to the Editor, pp. 1563-1565 and 1572.
69. Southworth, G. C., "Directive Microwave Radio Antenna," United States Patent Office, Feb 1, 1949, No. 2,460,401.
70. Small, J. G., Elchinger, G. M., Javan, Ali, Sanchez, Antonio, Bachner, F. J., and Smythe, D. L., "Ac Electron Tunneling at Infrared Frequencies: Thin-Film M-O-M Diode Structure with Broad-Band Characteristics," Appl. Phys. Letters, Vol. 24, No. 6, March 15, 1974, pp. 275-279.
71. Tani, Tatsuo, Electrotechnical Laboratory, Tanashi, Tokyo, Japan, Private Communication to Prof. R. L. Bailey, June 28, 1972.
72. Thornton, B. S., "Limit of the Moth's Eye Principle and Other Impedance-Matching Corrugations for Solar-Absorber Design," J. of Optics, Vol. 65, March 1975.


REFERENCES -(Cont'd.)

73. Twu, Bor-loug and Schwarz, S. E., "Properties of Infrared Cat-Whisker Antennas Near  $10.6 \mu$ ," Appl. Phys. Letters, Vol. 26, No. 12, June 15, 1975, pp. 672-675.
74. Twu, Bor-loug and Schwarz, S. E., "Mechanism and Properties of Point-Contact Metal-Insulator-Metal Diode Detectors at  $10.6 \mu$ ," Appl. Phys. Letters, Vol. 25, No. 10, Nov 15, 1974, pp. 595-598.
75. Van der Ziel, A., "Infrared Detection and Mixing in Heavily Doped Schottky Barrier Diodes," submitted May 30, 1975 to J. Appl. Phys.
76. Weit, James R., "Scattering of a Plane Wave from a Circular Dielectric Cylinder at Oblique Incidence," Canadian J. of Phys., Vol. 33, 1955, pp. 189-195.
77. Wilton, Donald R. and Raj Mittra, "A New Numerical Approach to the Calculation of Electromagnetic Scattering Properties of Two-Dimensional Bodies of Arbitrary Cross Section," IEEE Trans. Ant. & Prop., Vol. AP20, No. 3, 1972, pp. 310-317.
78. Young, Richard W., "Visual Cells," Scientific American, Oct 1970, pp. 81-91.
79. Zaki, Kawthar A. and Neureuther, Andrew R., "Scattering from a Perfectly Conducting Surface with a Sinusoidal Height Profile: TM Polarization," IEEE Trans. on Ant. & Prop., Vol. AP-19, No. 6, Nov 1971, pp. 747-651.
80. Zaki, Kawthar A. and Neureuther, Andrew R., "Scattering from a Perfectly Conducting Surface with a Sinusoidal Height Profile: TE Polarization," IEEE Trans. on Ant. & Prop., Vol. AP-19, No. 2, March 1971, pp. 208-214.
81. --- Catalogs, Emerson & Cumming, Inc., Microwave Products Div., Canton, Mass.
82. --- NSF/NASA Solar Energy Panel, Solar Energy as a National Energy Resource, December 1972, NTIS document No. PB 221-659.
83. --- "Reference Energy Systems and Resource Data For Use in the Assessment of Energy Technologies," submitted to the Office of Science and Technology, Executive Office of the President, Contract OST-30, Associated Universities, Inc. Upton, New York 11973, Document No. AET-8, April 1972.

## APPENDIX

### Research Results On Fire Ant Antenna

Proximal section - Consists of one long segment length 680 $\mu$ m, diameter 38 $\mu$ m to 73  $\mu$ m; 130 sensilla arrayed in an apparently random manner. — and with no specific orientation. Mean separation between sensilla 34 $\mu$ m; length of sensilla 37 $\mu$ m to 105 $\mu$ m. —

Center section - Consists of 7 segments - length 410 $\mu$ m and diameter of 28 to 63 $\mu$ m; length of sensilla 18 to 58 $\mu$ m; arrayed in a zig-zag manner , mean separation between rows on each segment 48 $\mu$ m.

Distal section - Consists of 2 segments - length 480 $\mu$ m. Densely populated with sensilla - still being studied.

Conclusion - Since the center section functions in trail following (narrow trail of scent laid by worker ants), and possesses an array arrangement, the  $2\lambda$  criteria for dielectric waveguides was applied to the zig-zag sensilla . —

$$\text{Max } 58 - \text{Min } 18 = 40\mu\text{m} = \frac{40\mu\text{m}}{2\lambda} = 20\mu\text{m}$$

### Experimental proof

Trail following scent from the fire ant was put into the interferometer source cell and modulated at 15 cps, the vibration frequency of the fire ant antenna. A sharp high intensity maserlike line emitted at 19.05 $\mu$ m. The intensity of the line could be increased by 20-fold by irradiating it with a sunlamp. According to NASA SP-8005 there is  $1.86 \times 10^{-2} \text{ W } \mu\text{m}^{-2}$  spectral irradiance from the sun at 19 $\mu$ m  $\lambda$ ., at a brightness temp. of 4675 T(K).

### Candle experiment

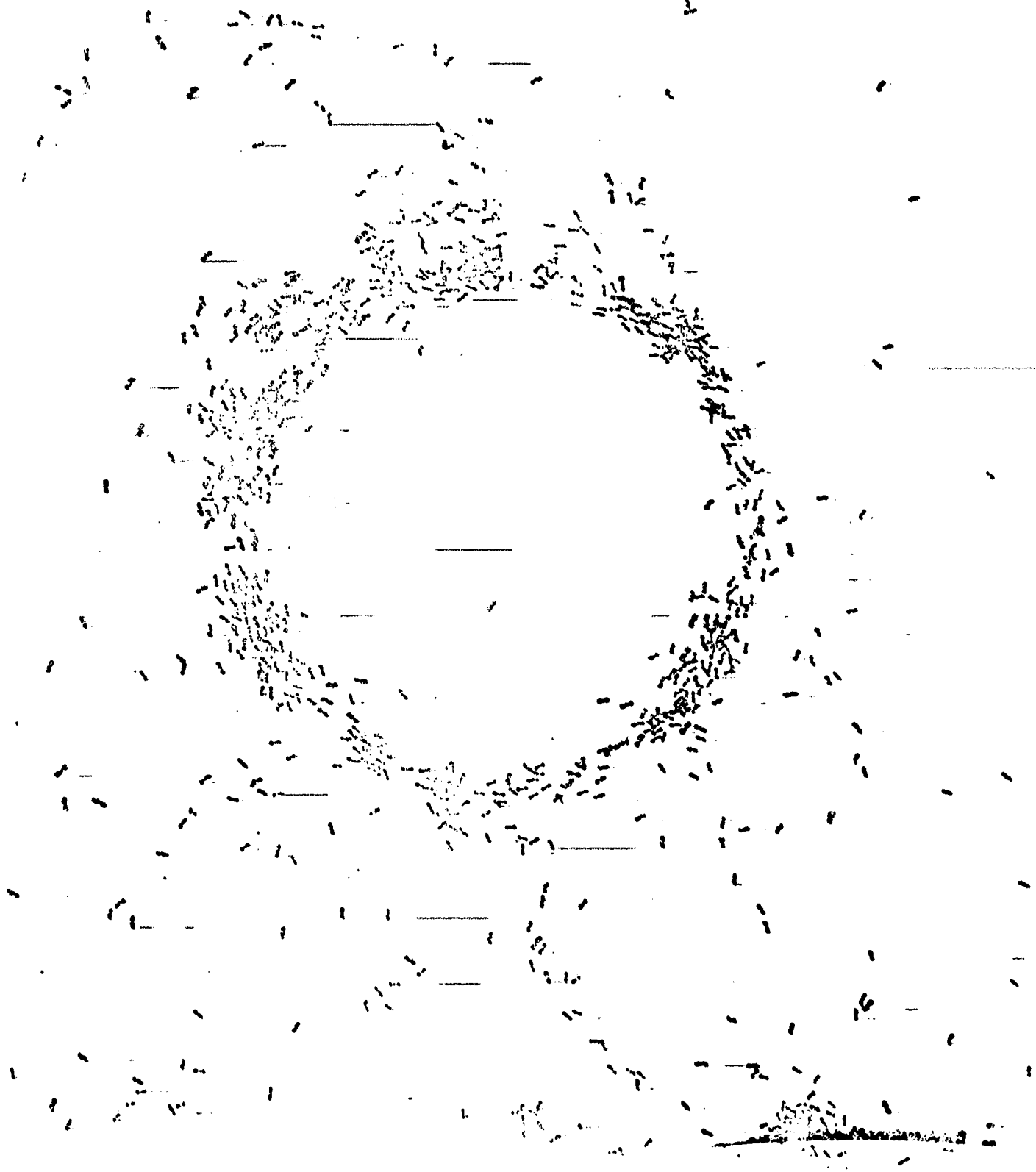
The line 19.05 was noted as coming from a candle flame. . Accordingly a candle was cut so that it was 1/4 inch above the floor. Ants released three feet from the candle went directly to the candle and ran round and round the flame in the same manner as moths fly to a candle. When a kerosene glass mantle was put over the flame so that the visible light passed, but the far IR was blocked, ants ignored the flame. Since a candle is analogous to the sun, this is further proof that the sun can be tuned to by dielectric spines. .

#### Attraction of Fire Ant to Candlelight (50 Ants)

	Response time in sec.	
	Min.	Max.
Candle alone	7	16
Glass mantle over candle	None	None
IR Transmitting plastic mantle	9	15

TRAIL SCENT LAID IN A CIRCLE

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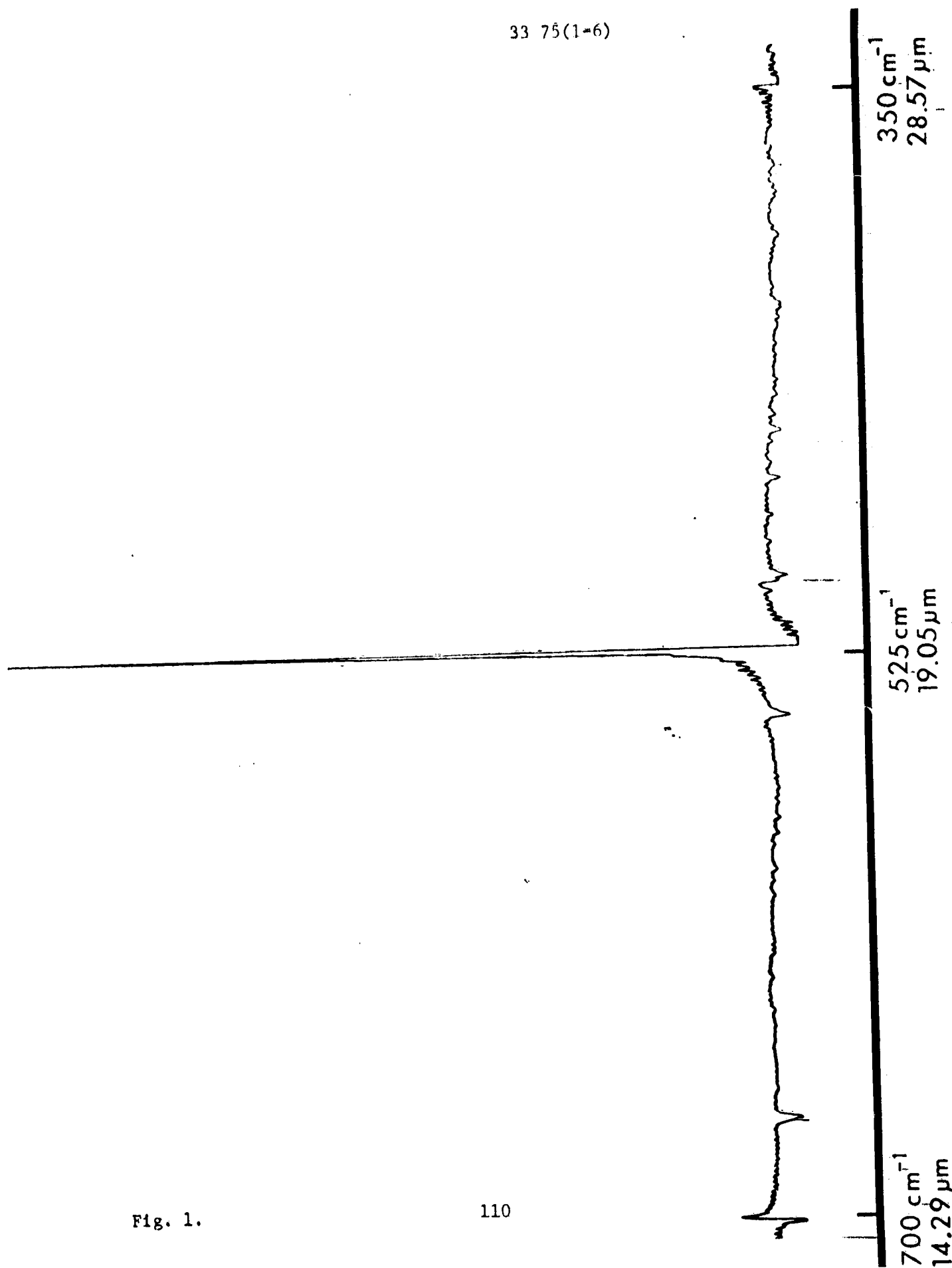


Fig. 1.